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School of Mechanical and Aerospace Engineering
Oklahoma State University

Final Report -- Contract EHS 70-103

DESIGN CRITERIA
FOR
HYDROGEN BURNING ENGINES

Prepared for
Environmental Protection Agency
Office of Air Programs
Division of Emission Control Technology
Ann Arbor, Michigan 48105

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Laboratory experiments have demonstrated hydrogen not only to be an excellent substitute for conventional hydrocarbon fuels in internal combustion engines but also to have the inherent qualities necessary for a permanent solution to the air pollution problem. This conclusion was reached after extensive tests were conducted with an air-cooled single-cylinder gasoline engine converted to run on hydrogen. The engine's operational characteristics compared favorable with those of its gasoline counterpart. Furthermore, the NOX content of the exhaust was an order of magnitude lower than that expected from a gasoline engine. Trace amounts of unburned hydrocarbons and carbon oxides, also present, originated from the lubricating oil. It was concluded from these experiments that a multi-cylinder automotive engine converted to run on hydrogen should be able to meet the 1975/76 Federal Emission Standards.

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FINAL REPORT--CONTRACT EHS 70-103

DESIGN CRITERIA FOR HYDROGEN BURNING ENGINES

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Environmental Protection Agency
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Ann Arbor, Michigan 48105

Attention: Mr. Charles Gray, Jr.
Project Officer

October, 1971

FOREWORD

This is the final report on research conducted at Oklahoma State University entitled, "Design Criteria for Hydrogen Burning Engines." The work was sponsored by the Office of Air Programs (formerly National Air Pollution Control Administration) of the Environmental Protection Agency, under Contract EHS 70-103.

The report covers work performed during the contract period from June 1, 1970 to September 30, 1971.

Respectfully submitted,

Roger J. Schoeppel

Roger J. Schoeppel
Project Director

ABSTRACT

Laboratory experiments have demonstrated hydrogen not only to be an excellent substitute for conventional hydrocarbon fuels in internal combustion engines but also to have the inherent qualities necessary for a permanent solution to the air pollution problem. This conclusion was reached after extensive tests were conducted with an air-cooled single-cylinder gasoline engine converted to run on hydrogen. The engine's operational characteristics compared favorable with those of its gasoline counterpart. Furthermore, the NOX content of the exhaust was an order of magnitude lower than that expected from a gasoline engine. Trace amounts of unburned hydrocarbons and carbon oxides, also present, originated from the lubricating oil. It was concluded from these experiments that a multi-cylinder automotive engine converted to run on hydrogen should be able to meet the 1975/76 Federal Emission Standards.

SUMMARY

A single-cylinder, spark ignition, air-cooled industrial engine was converted to hydrogen operation. The conversion was accomplished by addition of a second camshaft to actuate a double poppet valve controlling direct cylinder injection of gaseous hydrogen fuel. The objective of the work was to conduct comprehensive engine performance and emission tests in order to determine criteria for designing hydrogen burning multi-cylinder engines and turbines.

The hydrogen engine was operated intermittantly for a cumulative 48-3/4 hours. Its performance compared favorably with that claimed by the manufacturer for gasoline operation. In contrast to other published works, reliable hydrogen engine performance was achieved without pre-ignition or detonation. This was made possible through use of a patented process involving direct cylinder injection with combustion being initiated immediately upon hydrogen injection and continuing throughout the injection period. With these features, the engine could be reduced to a considerably lower idle speed than with gasoline fueling. By increasing the amount of hydrogen delivered during the injection period, it was possible to "drive" the engine beyond its design horsepower.

The principal emissions from a hydrogen fueled engine were found to be steam, the constituents of air, and nitrogen oxides. Some unburned hydrogen was also present. In addition, minor concentrations of carbonaceous compounds were present but could be reduced by making engine design

changes which minimize oil consumption. It is concluded from this work that the only pollutant of significance from a hydrogen fueled engine are compounds of nitrogen (NOX). The maximum NOX produced was 3.0 grams per brake-horsepower-hour (BHP-Hr) with 2.0 grams/BHP-Hr being about average for all levels of engine performance. (The inter-relationship of emissions and performance for the air-cooled experimental hydrogen engine is summarized in Figure 36. A similar graph of the experimental data for the water cooled version of this same engine is presented in Figure 37.)

Design criteria were established for improved mixing within the combustion chamber, ignition without occasional misfire, and effective heat removal. Other variables studied included design criteria for injection valving, glow ignition and NOX reduction.

ACKNOWLEDGEMENT

The Project Director wishes to especially recognize Mr. Charles L. Gray, Jr. under whose auspices the major portion of this work was done. His efforts as a professional in insuring that the project attained a high level of accomplishment are worthy of mention. Appreciation is also expressed to Dr. Richard G. Murray whose enthusiastic and capable assistance is reflected in the quantity and quality of work done. Contributions made by other members of the Project Team are also acknowledged. The efficient and helpful logistic support received from Mr. Raymond E. Chapel of Oklahoma State University and Mr. Martin K. Trusty of the Environmental Protection Agency was appreciated.

Appreciation is also extended for the loan of certain essential hardware items from NASA's Manned Space Craft Center and to the Phillips Petroleum Company for their assistance with the exhaust gas analyses.

TABLE OF CONTENTS

Page No.

Forward i
Abstract ii
Summary iii
Acknowledgement v

I. INTRODUCTION 1
- A. Background 1
- B. Program Scope of Work 4

II. ENGINE TEST APPARATUS 6
- A. Instrumentation 6
- B. Hydrogen Supply System 8

III. OXIDES OF NITROGEN APPARATUS 9
- A. Sampling System 9
- B. Infrared Analyzer 10

IV. THE HYDROGEN ENGINE 12
- A. Basic Design 12
- B. Operating Principle 13
- C. Characteristic Emissions 15

V. ENGINE TEST PROCEDURE 17
- A. General Test Procedure 17
- B. Low Power Experiments 19

VI. FIRST PHASE OPERATION AND PROBLEMS 21
- A. Test Procedure Problems 21
- B. Mechanical Problems 22
- C. Overall Operation 23A

VII. FIRST PHASE DATA AND DATA ANALYSIS 24
- A. Comprehensive Data 24
- B. Low Power Experimental Data 27
- C. Discussion 27

VIII. SECOND PHASE ENGINE MODIFICATION AND TESTING 31
- A. Engine Modification 31
- B. General 31

TABLE OF CONTENTS (Cont'd)

Page No.

C. Water Cooled Engine Tests and Data 31
D. Discussion and Data Graphics 32
IX. GASOLINE TESTS 34
X. COMPARISON OF EMISSIONS 35
XI. CONCLUSIONS 38
XII. RECOMMENDATIONS 40
XIII. CALCULATIONS 41
XIV. NOMENCLATURE 43
References 45

LIST OF FIGURES

Fig. No. — Page No.

1. Fuel-engine System Emissions 47
2. Fuel Characteristics 48
3. Engine Test Apparatus 49
4. Fuel Flowmeter Calibration Curve 50
5A. Nitric Oxide Sampling System Schematic 51
5B. Nitric Oxide Sampling System 52
6. Hydrogen Engine - Cast Iron Crank Case 53
7. Injection Mechanism Components 54
8. Disassembled Engine - Combustion Chamber 55
9. Valve Timing Diagram 56
10. Tree Diagram - OAP Data Format 57
11. Tree Diagram - Data Runs - Advanced Combination Angle 58
12. Engine Performance Characteristics 59
13A. Cylinder Pressure - Time Diagrams - Low & Intermediate Speed and Power 60
13B. Cylinder Pressure - Time Diagrams-Gasoline and Hydrogen Operation, Intermediate Speed, High Power 61
14. Tree Diagram of Low Power, Lean Fuel Experiments 62
15. Head Gasket Failure 63
16A. Tree Diagram - Oxides of Nitrogen Emission - OAP Format -2000 RPM 64
16B. Tree Diagram - Oxides of Nitrogen Emission - OAP Format -2500 RPM 65
16C. Tree Diagram - Oxides of Nitrogen Emission - OAP Format -3000 RPM 66
16D. Tree Diagram - Oxides of Nitrogen Emission - OAP Format - 3500 RPM 67
16E. Tree Diagram - Oxides of Nitrogen Emission - OAP Format -4000 RPM 68
17A. Emission-Mixture Relationships 69
17B. Emission-Mixture Relationships 70
17C. Emission-Mixture Relationships 71
17D. Emission-Mixture Relationships 72
17E. Emission-Mixture Relationships 73

LIST OF FIGURES (Cont'd)

Fig. No.		Page No.
17F.	Composite Plot of Figures 17A - 17E	74
18A.	Power-Mixture Relationships	75
18B.	Power-Mixture Relationships	76
18C.	Power-Mixture Relationships	77
18D.	Power-Mixture Relationships	78
18E.	Power-Mixture Relationships	79
18F.	Composite Plot of Figures 18A-18E	80
19.	Emission Concentration	81
20A.	Emission-Power Relationships	82
20B.	Emission-Power Relationships	83
20C.	Emission-Power Relationships	84
21.	Exhaust Gas Temperature	85
22A.	Emission-Mixture Relationships	86
22B.	Emission-Mixture Relationships	87
23.	Wide-Open Throttle Emission Characteristics	88
24.	Comparative Emissions-Mass Basis	89
25.	Water Jacket Engine Modification	90
26.	Tree Diagram-Water Jacketed Data Runs	91
27A.	Power-Mixture Relationships - Water Jacketed Engine	92
27B.	Power-Mixture Relationships - Water Jacketed Engine	93
27C.	Power-Mixture Relationships - Water Jacketed Engine	94
27D.	Power-Mixture Relationships - Water Jacketed Engine	95
27E.	Power-Mixture Relationships - Water Jacketed Engine	96
27F.	Composite Plot of Figures 27A - 27E	97
28A.	Emission-Mixture Relationships - Water Jacketed Engine	98
28B.	Emission-Mixture Relationships - Water Jacketed Engine	99
28C.	Emission-Mixture Relationships - Water Jacketed Engine	100
28D.	Emission-Mixture Relationships - Water Jacketed Engine	101
28E.	Emission-Mixture Relationships - Water Jacketed Engine	102

LIST OF FIGURES (Cont'd)

Fig. No. | Page No.

28F. Composite Plot of Figures 28A-28E 103
29A. Tree Diagram- Water Jacketed Engine Emissions - OAP Format 104
29B. Tree Diagram - Water Jacketed Engine Emissions - OAP Format 105
29C. Tree Diagram - Water Jacketed Engine Emissions - OAP Format 106
29D. Tree Diagram - Water Jacketed Engine Emissions - OAP Format 107
29E. Tree Diagram - Water Jacketed Engine Emissions - OAP Format 108
30A. Emission-Mixture Relationship - Advanced Combination Angle 109
30B. Emission-Mixture Relationship - Advanced Combination Angle 110
30C. Emission-Mixture Relationship - Advanced Combination Angle 111
30D. Emission-Mixture Relationship - Advanced Combination Angle 112
30E. Emission-Mixture Relationship - Advanced Combination Angle 113
31A. Power-Mixture Relationship - Advanced Combination Angle 114
31B. Power-Mixture Relationship - Advanced Combination Angle 115
31C. Power-Mixture Relationship - Advanced Combination Angle 116
31D. Power-Mixture Relationship - Advanced Combination Angle 117
31E. Power-Mixture Relationship - Advanced Combination Angle 118
32A. Emission-Mixture Relationship - Retarded Combination Angle 119
32B. Emission-Mixture Relationship - Retarded Combination Angle 120
32C. Emission-Mixture Relationship - Retarded Combination Angle 121
32D. Emission-Mixture Relationship - Retarded Combination Angle 122
32E. Emission-Mixture Relationship - Retarded Combination Angle 123
33A. Power-Mixture Relationship - Retarded Combination Angle 124
33B. Power-Mixture Relationship - Retarded Combination Angle 125
33C. Power-Mixture Relationship - Retarded Combination Angle 126
33D. Power-Mixture Relationship - Retarded Combination Angle 127
33E. Power-Mixture Relationship - Retarded Combination Angle 128
34. Engine Emissions (From Tables 5 and 7) 129
35. Engine Emissions (From Tables 5 and 7) 130
36. Engine Emissions Versus Performance, Air-Cooled Engine 131
37. Engine Emissions Versus Performance, Water-Cooled Engine 132

LIST OF TABLES

Table No.		Page No.
1.	Engine Specifications	133
2.	Engine Operational Data--First Sequence	134, 135, 136
3.	Engine Test Form	137
4.	Engine Operational Data--Low Power Experiments	138
5.	Comprehensive Exhaust Gas Analysis - Air Cooled Engine	139
6.	Engine Operational Data--Water Jacketed Engine	140, 141
7.	Comprehensive Exhaust Gas Analysis--Water Jacketed Engine	142
8.	Engine Operational Data - Gasoline Tests	143
9.	Comprehensive Exhaust Gas Analysis - Gasoline Tests	144

DESIGN CRITERIA FOR HYDROGEN BURNING ENGINES

I. INTRODUCTION

A. Background

Interest in usage of hydrogen as an energy fuel has developed from man's concern over society's environmental crisis. It has become evident that combustion of fossil fuels and waste burning must be controlled if satisfactory ambient air quality is to be obtained. Two primary problems are associated with the use of fossil fuel: 1) atmospheric pollution and 2) mineral fuel depletion.

Atmospheric pollution has become of international concern during the past several years and is primarily attributed to the burning of fossil fuels to produce energy. This burning removes oxygen and nitrogen from the atmosphere and replaces them with carbon dioxide, carbon monoxide, water vapor, the oxides of nitrogen and oxygenated organic compounds (See Figure 1). Exposure to some of these compounds can cause damage to personal health and property, a problem which is intensified in urban areas. The internal combustion engine has become the most serious offender in past years, reportedly causing up to 60 percent (in certain areas at peak periods) of all air pollution. With a growing population and an increase in the basic standard of living, the associated consumption of energy, viz. the burning of fossil fuel, is increasing at a rapid rate. Therefore, it becomes most important that mankind not only becomes concerned about air pollution but also that he formulate definite corrective actions to eliminate the problem.

The supply of fossil fuels in the world is limited. Since mankind has been consuming fossil fuels at an exponentially increasing rate, the time is fast approaching when their rate of depletion will exceed the discovery of new supplies. This has already happened for the United States, which now has to import almost one of every three barrels of oil it needs. Since coal, natural gas, and other conventional supplies cannot be depended on to make up the national needs, there has developed an energy supply gap which is nearing "crisis" proportions.

The above reasons indicate why society should be concerned that future supplies of energy are available in a non-contaminatory, non-depletable form. Nuclear power systems eliminate most of the pollution-depletion problem associated with fossil fuels and have recently received renewed emphasis by the Nixon administration. The supply of nuclear fuel is quite extensive if low grade ores are considered. However, unless the breeder reactor becomes practical, nuclear power will not provide a very practical-continuing energy supply. Combined with this is the improbability that nuclear power will be applicable to small mobile power plants.

A conceivable answer to the mobile power plant portion of the fuel depletion-pollution problem is the generation and use of a synthetic fuel such as hydrogen. Hydrogen can be generated by electrolysis of water into hydrogen and oxygen. It has both excellent combustion characteristics and a desirable energy to weight ratio (see Figure 2). Relative to hydrocarbon fuel, hydrogen's use as a fuel would not contribute to air pollution.

since the only air contaminant would be oxides of nitrogen and these occur with any combustion process involving air. Fortunately, however, the wide flammability limits of hydrogen offer the opportunity of reducing this pollutant to considerably lower levels than now exist with fossil-fueled engines.

If hydrogen is seriously considered as a mobile power plant fuel, then a system for its safe distribution, its handling and storage must be developed. Fortunately, much progress has been made in the storage of hydrogen within the last few years. Super insulated cryogenic tanks are now manufactured that permit the storage of liquid hydrogen with less than 0.5 percent per day boil-off. Also, recent work at Brookhaven National Laboratories has shown that hydrogen may be more practically stored as a metal hydride.[1] For example, hydrogen reacts with various metals and alloys such as magnesium-nickel or magnesium-copper to form hydrides. To effect its release, heat is supplied to the hydride which in turn decomposes evolving hydrogen in gaseous form. In this case, the hydride could be stored in a container in the form of a bed of fine particles, with the hydrogen being evolved at any desired temperature above 550°F. The pressure of the hydrogen produced depends upon the equilibrium temperature of the metal hydride.

If an adequate supply of hydrogen could be developed, mankind would have solved both of the problems mentioned earlier. It is technically possible to produce large quantities of hydrogen by electrolysis during periods of "off-peak" power operations. This could be a significant percentage of each day's output and allow the power companies to operate more efficiently. The electrical demand of large scale electrolysis could be met by new nuclear power plant installations.

From a cost standpoint, and depending on the "price of pollution," hydrogen is becoming more attractive as a fuel. The present price for liquid hydrogen in large quantity purchases is approximately fifty cents per pound. This makes it about ten times the cost of gasoline on a BTU basis. However, this price reflects a major expense for liquification which would not be necessary in hydride storage. Full scale production of hydrogen could reduce its cost considerably as has been shown by prior economic studies.[2] Thus the cost outlook for hydrogen appears increasingly optimistic. In contrast, the price of gasoline is expected to increase due to the added refining expense to produce comparable quality non-leaded gasoline and will undoubtedly undergo continual price increases as petroleum becomes more scarce.

As a fuel, hydrogen could be used in either internal combustion engines or fuel cells. Because of the low cost per horsepower, the high power output to weight ratio, and the extended range of operation of internal combustion engines, the hydrogen-fueled internal-combustion engine appears most promising.

B. Program Scope of Work

For the past three years research has been conducted at Oklahoma State University to evaluate problems associated with producing a practical hydrogen fueled engine. During this time, several engines have been converted to hydrogen operation.[3-10]

Financial assistance in this effort has been aided by the Office of Air Programs, Environmental Protection Agency, since 1 June 1970. It is the purpose of this document to describe the work performed under contract EHS 70-103 between 1 June 1970 and 30 September 1971 in fulfillment of the following specific objectives:

Phase 1) Conduct comprehensive engine performance and emission tests for nitrogen oxides using hydrogen to fuel a single cylinder prototype engine over its range of speed and power output.

Phase 2) Analyze the data obtained in Phase 1, above, then redesign and retest the engine as possible within the remaining time and funds.

The overall objective of the work was to conduct comprehensive engine performance and emission tests in order to determine design criteria for designing hydrogen burning multi-cylinder engines and turbines.

II. ENGINE TEST APPARATUS

The engine test apparatus is shown in Figure 3. The engine and dynamometer were mounted on a laboratory bench which was equipped with an isolation panel to increase operator safety. This panel was fabricated of a plywood steel laminate with a steel framework. The central portion of the panel was provided with an observation window which consisted of two one-inch thick plastic sheets separated by two sheets of automotive safety glass. The right section of the panel served as a support for the hydrogen delivery system which consisted of a supply valve, a pressure regulator, and a purge and leak detection system.

A water absorption type dynamometer was installed directly on the test bench. This dynamometer was equipped with a load meter, tachometer, and throttle and absorption load controls. Load (and consequently speed) control of this type dynamometer is somewhat sensitive to inlet water pressure and therefore some difficulty was experienced in keeping a constant RPM over any prolonged period of engine testing.

A. Instrumentation

Engine intake air was measured with an ASME long radius nozzle attached to a pulse damping drum. Wind gust impingement on the nozzle entrance gave erratic air flow measurements during preliminary tests. However, relocation of the nozzle to the inside of the test cell eliminated this difficulty.

A heat transfer sensitive meter was utilized to measure hydrogen flow. This meter was given a static calibration (steady rather than pulsating flow)before installation and yielded excellent initial results. Once this meter was subjected to dynamic conditions, however, it proved extremely unreliable. After lengthy analysis it was determined that the meter was sensitive to average injection pressure, electrical interference from the ignition system, and pressure pulsations in the delivery line.

A large volume high pressure test tank was used for hydrogen meter calibration. By measuring the time for a given pressure change (no noticeable temperature changes occurred during this time), the mass of hydrogen removed from the tank could be calculated by using the ideal gas law with the compressibility factor. The results of this calibration are shown in Figure 4.

During initial tests, cylinder head, crankcase, and exhaust gas temperatures were measured and recorded by a multiple point recorder. The exhaust gas temperatures, however, required the use of a chromel-alumel thermocouple for this one parameter. Cylinder head and crankcase temperature recordings were discontinued at this time since the recorder was not compatible with different thermocouple types. Engine cylinder pressure was obtained from a transducer mounted in communication with the combustion chamber. The output of this device was displayed on an oscilloscope in the form of a pressure-time diagram. (see, for example, Figures 13A and 13B).

B. Hydrogen Supply System

Gaseous hydrogen in high pressure bottles was used for the fuel source. These were attached to a common manifold and delivered hydrogen to a series of valves and controls located on the isolation panel. A nitrogen purge system was added for safety purposes.

III. OXIDES OF NITROGEN APPARATUS

As supported by previous observations,[11] nitric oxide (NO) apparently undergoes little oxidation to the dioxide by the time it is exhausted fron an internal combustion engine. Thus, NO was assumed to be the primary nitrogen oxide present in the exhaust system. Accordingly, only NO measurements were made and the data are reported as NOX on this basis. The validity of this assumption is further supported by the fact that experimental transport times were of less than 20 seconds duration.

A. Sampling System

Figures 5A and 5B show details of the sampling system which delivered the raw exhaust gas sample to the analyzer. This system was designed and fabricated in such a way so as to allow the analysis to be completed within 20 seconds after the gas was exhausted from the combustion chamber of the engine. Not shown on the diagram is the exhaust mixing tank used to insure that a representative sample was taken from the engine.

The sampling system consisted of a pump, control valves, flow meter, refrigerator, and dryers. The exhaust after leaving the engine was cooled to 32°F, where the excess water was condensed leaving the gas in a cooled and saturated condition. A portion of this saturated gas was vented with the remainder passing through the analyzer. The rate of venting was controlled so that the desired flow of sample gas through the analyzer was maintained. In the flow train, the sample gas was dryed by passage through a Drierite bed containing both indicating and non-indicating sections. It was then delivered to the analyzer. This sample then was finally metered for flow rate before dumping to the outside. The pump flow rate was maintained at a high level so that minimum time was needed for the sample to travel from the mixing tank to the analyzer. Response time between a change in engine operation and a change in analyzer reading was less than 20 seconds.

Accessory to the sampling system were four cylinders of gas (1-zero, 3-calibration) needed for zero and range calibration of the analyzer.

B. Infrared Analyzer

Analyses for NO were obtained with a Beckman Model 205 AL 3-range (0-100, 0-500, 0-1000 PPM) infrared analyzer. The manufacturer's recommendations for design of the sampling system were followed resulting in the system just described. In this design it was recommended that 1) a separate calibration gas be used for each range, 2) the zero and span calibration gases be introduced through the same drying system as the sample to be measured, and 3) a refrigerated condenser be used in conjunction with the drying tubes. Calibration gases (consisting of a mixture of NO in N_2) were ordered for 90 PPM ± 9PPM, 450 PPM ± 45PPM, and 900 PPM ± 90PPM. The gases supplied were certified to contain 94PPM, 468 PPM and 935PPM NO, respectively. The zero gas was prepurified N_2.

The repeatability in percent of full scale was stated by the manufacturer to be:

Range No.	PPM Range	% of F.S.
1	0 - 1000	1.0
2	0 - 500	1.0
3	0 - 100	2.0

Calibration charts were furnished with the instrument for atmospheric pressure operation. Since all measurements were made at atmospheric pressure, these charts were directly useful.

The recommended procedure for calibration of the instrument as specified in Instruction Manual 81635-C and modified by revision dated August, 1970, were followed. Basically this consisted of first using the range 1 calibrating gas to set the initial upscale standardization point. Then the calibration gas appropriate for range 2 (or 3) was passed through the instrument and the upscale standardization point checked for this gas. Initially, and twice during the four months of operation, the oscillator required tuning in order to obtain the calibrated instrument response.

In summary, this device yielded "good" response and "stable" operation insofar as is known or as was inferred from operation of the instrument according to the manufacturer's recommended procedure. By "good" response is meant the time required for the instrument to respond to changes in concentration of NO, and by "stable"operation is meant that the instrument did not drift in meter output. The "response time" of 20 seconds mentioned above was with respect to the entire measuring system and includes the just discussed response time of the instrument.

IV. THE HYDROGEN ENGINE

A. Basic Design

In order to minimize thermal expansion and provide a more wear-resistant cylinder (in comparison with the earlier aluminum engines), a cast iron crankcase engine, as specified in Table 1, was selected for conversion.

The crankcase of this engine was modified by weld insertion of a cam housing to provide room for a second camshaft (see Figure 6). This camshaft was used to actuate the hydrogen injection valve through a series of cam followers, pushrods (see Figure 7), and rocker arms. Both injection start and injector gate angles (which control the time and duration of hydrogen injection) were adjustable by either stepping the camshaft gear on the crankshaft through a tooth configuration or by rotating the cams on the camshaft.

Ignition contact breakers were placed in a movable housing in such a way that ignition timing could be adjusted. These contact breakers were connected to a normal automotive ignition system and the standard magneto provided by the manufacturer for this engine was removed.

A water jacket was added to the engine after most of the experimental data had been taken in a successful effort to reduce the effects of localized heating. Intake valve oil seals were also added at this time. (The water jacketed engine is discussed in detail in Chapter VIII.)

Hydrogen flow was metered by a dual poppet valve which was contained in a housing attached to the cylinder head. From the valve the hydrogen passed through a stainless steel tube (see Figure 8) directly into the cylinder. Distribution ports in this tube distributed the hydrogen throughout the air charge located in the combustion chamber.

Other design details associated with this installation of note are: an electric starting system, a water spray cooling system, an index wheel-strobe light timing system, visual oil indicator, and a manual injector lubricator. It should be noted that the carburetor was used only for a throttling device· all other flow passages were blocked before hydrogen operation.

B. Operating Principle

The basic four cycle operating characteristics of the Clinton engine were unchanged. Air alone was inducted and compressed, while gaseous hydrogen was injected and ignited near the top dead center (TDC) piston position. Injection continued during the early portion of the expansion stroke (see Figure 9 for engine valve timing details). Finally the products of combustion were exhausted and the operational cycle repeated. (Clearance gases, trapped in the cylinder at the end of the exhaust stroke, should be high in water vapor content and may have aided engine operation significantly.)

Findings reported herein for the "hydrogen engine" must be qualified with respect to the specific design used in construction of the engine. In this case, a conventional gasoline engine was converted to operate on hydrogen according to the inventive scheme described in U.S. Patent 3,572,297.[5] The basic improvement over the conventional carbureted engine is the provision of means for injecting gaseous fuel directly into the cylinder. In application, air is inducted and compressed with hydrogen being injected near the top dead center position of the piston. This sequence of operations allows the following capabilities:

Feature:

1. control of the nature of the gases accumulating in the crankcase
2. control of the nature of the gases in the induction manifold
3. control of the time hydrogen is introduced into the cylinder
4. control of the duration of hydrogen injection
5. control of the rate of hydrogen injection
6. control of the time ignition first occurs
7. control of the combustion reaction during the injection period
8. control of the mass of the working fluid within the cylinder
9. control of the specific heat of the working fluid

The OSU engine was designed to take advantage of these capabilities insofar as was practical in the prototype development. The design approach allowed control over pre-ignition since the fuel was intentionally ignited immediately upon entry into the cylinder (Feature 6). It was possible to design around the detonation problem, also reported by other workers in the field, by controlling the rate of fuel and oxidant consumption during the combustion period (Feature 7). These design options in conjunction with those offered by Features 3, 4, 5, 8 and 9 allow control of engine power. In general it was expected that the performance of the hydrogen engine would be equal to or surpass that of its gasoline counterpart. Also, the undesirable emittants were expected to be limited to oxides of nitrogen since the condition of combustion could not be expected to allow any but a negligible portion of the lubricating oil to be consumed. Finally, Features 1 and 2 preclude the accumulation of explosive gaseous mixtures in locations where their ignition could lead to unsafe engine operation.

C. Characteristic Emissions

Emissions from internal combustion engines varies as a function of the air-fuel ratio. For gasoline engines, low NOX emissions may be achieved by either operating very lean or very rich. In contrast, however, carbon monoxide (CO) and hydrocarbon(HC) emissions can be minimized only by operating lean. Unfortunately, the narrow flammability limits of gasoline prohibit operation beyond the approximate air-fuel ratio values of 10:1 to 17:1. Thus engine misfire and poor performance result at the lean operating conditions required for low emissions of all three undesirable constituents: CO, HC, and NOX.

In contrast to emissions from the gasoline engine, the hydrogen engine is capable of operating over much wider air-fuel ratios. This is due to the wide flammability limits of hydrogen which are from 4 percent to 74 percent in air. By operating in the lean regions, the combustion temperature can be controlled depending on the air-fuel ratio. This is apparently related to the specific heat of the reactant and product gases. Since the reaction temperature is reduced, the NOX would also be expected to be reduced. In addition, the low level of radiation exhibited by a hydrogen flame reduces the heat transfer by this mechanism to the other cylinder gases. Consequently, the heat generated by combustion is primarily limited to convection for its distribution to the non-combustible components of the working fluid.

V. ENGINE TEST PROCEDURE

A. General Test Procedure

The OAP Project Officer requested engine emissions data for a minimum of 81 data points as illustrated by Figure 10. Specifically, it was requested that data be taken at the following conditions: 1) for each injector gate angle operate the engine at three RPM's; 2) for each RPM operate the engine at three air-fuel ratios; 3) for each air-fuel ratio operate the engine for three ignition timings; 4) for each ignition timing operate the engine at three load conditions. Emission analyses were required for NOX with the measurement of other emissions requested on an optional basis. In addition, the following information was requested: engine, characteristics and history; gas analysis technique; and type of fuel.

Since it would be extremely difficult to hold the air-fuel ratio constant during the tests, permission was granted to conduct the tests as shown by the first three columns of Figure 11 with the previously requested data to be obtained from cross interpolation. Also, since ignition timing has little meaning unless correlated with injector gate angle, permission to test at three values of injection start, ignition timing, and injection termination, rather than just at three ignition timings, was requested and granted. Hereafter, the combination of the three angles controlling the injection period and timing for ignition will be referred to as the combination angle. The three combination angles chosen were (+44°, +20°, and -19°); (+28°, +7°, and -38°); and (+14°, 0°, and -60°). They were manually set and had no provision for automatic adjustment.

Figure 12 shows the engine manufacturer's stated wide-open-throttle (WOT) rating and the converted hydrogen engine's power characteristics. The difference between the two curves represents the power loss caused by addition of the various mechanisms required to control hydrogen injection. It should be recognized that the modified WOT engine horsepower curve was arbitrarily determined by designing for a one horsepower loss at peak performance conditions. (From experience with a similar size engine, it was determined that the injection mechanism required about one brake horsepower for its operation. In order to make a comparison of hydrogen and gasoline operation, the hydrogen injected was controlled to achieve this amount of derated brake horsepower. This procedure was implemented since hydrogen can be injected to give an engine output greater than 100 percent of its design brake horsepower if desired.) This procedure was necessary in order to establish a range in power levels which could be repeated in subsequent tests. The experimental conditions necessary to obtain this design maximum were determined by injecting increasing quantities of hydrogen until the power output of the engine reached the design maximum power at that RPM. For reduced load testing, and for each level in RPM, the power level was reduced to 65 percent and 35 percent of the maximum value at that RPM and the fuel was again delivered to force the engine's output to these reduced values.

It was decided to take data at five engine speeds instead of the three requested so that the interpolated values at specific conditions would be more accurate. Engine speeds selected were 2000, 2500, 3000, 3500 and

4000 RPM's. The basic information, then, consists of emissions and performance data at five engine speeds for each of three power levels. Thus, these fifteen runs were repeated for each of three relative air flows: maximum air flow at a given RPM, 80 percent, and 70 percent of that maximum air flow. This procedure yielded variable air-fuel ratio data at each RPM and power level. When these 45 runs are repeated for each of three combination angles a total of 135 experimental runs were required. Data taken for each run included: NO emission, dynamometer force, RPM, exhaust gas temperature, manifold vacuum, hydrogen flow rate, air flow rate, ignition timing, injection pressure, air temperature, and barometric pressure.

Cylinder pressure-time diagrams were observed during all testing. Three such diagrams for low, intermediate, and high power operation are shown in Figures 13A and 13B.

B. Low Power Experiments

A series of low power, lean fuel, experiments were devised to more accurately characterize the engine's emissions as a function of its performance in this region. Investigations of this nature are important since automotive engines are frequently operated at loads less than 35 percent power.

An outline showing values selected for experiments in this region is presented in Figure 14. In addition to requesting this emphasis, the Project Officer also requested that a complete analysis be made of the exhaust gases for a few of the engine test conditions. As shown for each of five engine speeds, and for a specific level in the rate of fuel injection, the rate of air flow was varied. Its effect on engine power can be found by referring to the tabulated data in the Tables. At each of the low power region WOT runs, liter bottle samples of exhaust gas were collected and delivered to Phillips Petroleum Company's research laboratory for analysis. Two higher power samples were also taken for comparison of emissions from higher power runs. These corresponded to 65% power at 3000 and 3500 RPM engine speeds and WOT operation.

VI. FIRST PHASE OPERATION AND PROBLEMS

The greatest difficulty encountered in acquiring quality data was with the response and reliability of hydrogen flow instrumentation. However, other problems arose due to the constraints of the test procedure and mechanical limitations. The instrumentation problem has been previously discussed.

A. Test Procedure Problems

For experimental convenience, the procedure for first phase engine tests was limited to operation at one ignition timing with variable gate angles. As is explained below, this caused both loss of power and engine knock for certain combination angles. For best operation with smooth knock-free combustion, the hydrogen must be ignited immediately after entry into the combustion chamber. If the ignition spark is too far advanced within any injection gate angle, the hydrogen will arrive at the ignition source (spark plug) after the spark and a misfire will occur. This was observed for many low speed, low injection pressure runs where injection pressure was insufficient to drive the hydrogen to the spark plug by the time of ignition. If, on the other hand, the hydrogen injection pressure is relatively high (as in high RPM, high power runs), then hydrogen flow into the combustion chamber is rapid and significant concentrations collect before the spark. This condition results in engine knock with a corresponding increase in engine temperature and a decrease in power level. As will be shown in the discussion of "second phase engine modification and testing," smooth knock-free operation was obtained when the gate angle was fixed and the timing adjusted at each speed and power level.

B. Mechanical Problems

Basically, the mechanical problems encountered can be divided into two catagories: 1) those due to experimental variations in the basic design, and 2) those caused by operation of the engine under severe stress conditions.

In the first catagory, two significant problems which occured were due to injection cam index ring failure and localized overheating. The teeth of the cam index ring were purposely designed for minimum tooth width in order to have maximum flexibility in injection angle selection. Unfortunately, these indexing teeth failed under prolonged high speed operation and the camshaft was redesigned with a spring pin adjustment to replace the index teeth. Subsequent operation with this new design has been satisfactory.

The second problem developed apparently because the number and spacing of holes in the injector tube allowed the heat released to be concentrated in isolated areas. Thus, the thermal conductivity of the cast iron cylinder, while subjected to only air cooling, was insufficient to carry the heat away. As a result, localized hot spots developed under moderate and high power operations. Specifically, it was observed that the area of the cylinder adjacent to the exhaust valve and exhaust port attained extremely high localized temperatures while the opposite side of the cylinder remained relatively cool. This resulted in both compression and power losses as well as oil infiltration past the rings. This condition in turn caused generally higher fuel requirements and a noticeable oil consumption. In addition, the high temperature of the adjoining intake port reduced volumetric efficiency and attributed to difficulty in attaining steady-state operation during long high-power runs. As a result, high-power run length had to be shortened and data reproducibility was accordingly affected. This experimental limitation was overcome in second phase engine tests by provision of water cooling.

The second mechanical problem, caused by forcing the engine to operate under severe stress conditions (prolonged knocking)--which by no means could be considered "normal" or "recommended" operating conditions--was loss in engine power. The low thermal conductivity of the cast iron engine block probably helped aggravate the situation. In this case, operation under knocking conditions contributed to the localized hot spots previously described. These excessive temperatures in turn caused deterioration of the asbestos cylinder head gasket material. When the weakened gasket was subjected to repeated pressure pulses caused by combustion knock, it failed by progressively increasing leak rates until engine operation was no longer possible. Figure 15 shows such a gasket condition.

It should be pointed out that these mechanical limitations were all overcome by redesign and that no operating problems were encountered which could be specifically attributed to the hydrogen fuel.

C. Overall Operation

In general, operation of this engine was smooth except near the flammability limits or whenever the spark was either too early (resulting in misfire) or too late (when detonation occurred). All of the engine tests were made with spark ignition although hot wire and compression ignition were also found to give successful operation. The engine was easy to start and gave knock-free performance under significant power loadings for prolonged periods. It ran smoothly under load up to 5000 RPM which is above the maximum design operating speed of 4000 RPM for which it was designed. The low flammability limit of hydrogen in air allowed smooth-steady engine idling down to 1100 RPM whereas the engine could not be operated at less than 2200 RPM when fueled with iso-octane.

The temperature of the exhaust from the hydrogen engine, as measured at a point just downstream from the exhaust valve, varied between 500°F and 1700°F. Although "hot spots" developed within the combustion chamber as a result of the flame being "jetted" to prescribed locations, it should not be misconstrued that the engine's overall temperature was also "hot." In general, the engine's operating temperature with hydrogen fuel was observed to be comparable to or cooler than that produced with iso-octane fuel under similar speed and power loadings.

VII. FIRST PHASE DATA AND DATA ANALYSIS

A. Comprehensive Data

Table 2 lists data compiled for the sequence of runs associated with the first phase experiments. Basic engine operational data were as recorded on the record sheet of Table 3. Pertinent information was then transferred to IBM cards for automatic data processing. The computed results are those of Table 2. Computations were made as shown under Calculations. Missing numbers indicate data runs which were excluded because of possible errors in recording the basic data. An explanation of the nomenclature used in the headings of Table 2 follows. Further definitions are listed under Nomenclature.

Column Number	Description
1	Run number
2	Engine-speed, revolutions per minute
3	Brake power output, horsepower
4	Brake torque, foot pounds
5	Air-fuel ratio
6	Total oxides of nitrogen emissions, parts per million
7	Per cent throttle
8	Brake thermal efficiency, percent
9	Ignition angle, degrees
10	Manifold vacuum, inches of mercury
11	Brake specific fuel consumption, pounds per horsepower hour
12	Brake mean effective pressure, pounds per sq. inch
13	Air-flow, pounds per hour
14	Fuel-flow, pounds per hour
15	Exhaust gas temperature, degrees Fahrenheit
16	Cylinder-head temperature, degrees Fahrenheit
17	Crankcase temperature, degrees Fahrenheit
18	Percent stochiometric air
19	Percent maximum power
20	Percent maximum brake mean effective pressure
21 and 22	Injection gate angle
23	Minimum ignition angle for best torque(MBT), degrees
24	Total oxides of nitrogen emission, grams nitric oxide per brake horsepower hour
25	Injection pressure, pounds per square inch

The data of Table 2 for the first phase experiments show the NOX emissions normalized to account for the size of the engine, i. e. gms NOX/BHP-Hr. Such computations are normally made so that the emissions are on an "indicated" horsepower basis. Accordingly, it should be realized that "brake" horsepower was used in computations shown in this report and that the brake horsepower of an engine will always be less than the indicated horsepower by a factor that depends on the mechanical efficiency. Consequently, the recorded values of gms NOX/BHP-Hr are proportionately larger than they would be if they had been computed on an indicated horsepower basis.

Since the engine's power characteristics were requested in terms of percent maximum brake mean effective pressure (BMEP), it was necessary to establish this base under full power operation. This condition was evaluated to be 75.4 psi at 3000 RPM from theoretical design considerations. (Actual engine tests under nearly full loading produced a BMEP of 77 psi and could have been "driven" higher if desired. For simplicity however, the 75.4 psi BMEP will hereafter be considered as a base.)

Figures 16A through 16E presents the preliminary results of crossplot interpolations to obtain data in the form requested by OAP for the intermediate combination angle of 28°, 7°, -38°. The values shown for the emissions from the engine under different operating conditions (in terms of grams NOX per brake horsepower hour) were determined from crossplots of the experimental data plotted in Figures 17A through 17E. (A composite plot of Figures 17A-17E is presented in Figure 17F to show that the total variation in emissions for all of these preliminary experiments was less than 3.0 grams NOX/ BHP-Hr.) Associated values for the level of engine load (in terms of percent BMEP) were taken from crossplots of the data presented in Figures 18A through 18E. (A composite plot of the data contained in Figures 18A-18F. This plot is included in the report to illustrate the consistency obtained in the experimental data which in turn provides some idea of the data quality.) In addition to the conditions stated, each curve of Figures 17A through 17E, as well as those of Figures 18A through 18E, represents experimental conditions where the air intake was also maintained constant. Thus the "100% air" curves were taken at wide open throttle (WOT). The "80% air" and "70% air" curves represent experimental conditions where the volumetric air flow was 80% and 70% respectively of the WOT air flow. (It should be noted that because this was a fuel injected engine, the throttle controls air flow only with fuel flow being independent of the throttle setting.)

As an example of how any particular data reporting point would be determined, take the point specified as follows:

combination angle...............intermediate (28°, 7°, -38°)
RPM...........................2,000
air-fuel ratio...................stoichiometric
air flow.......................100% of maximum

First refer to Figure 17A which portrays NOX for any air-fuel ratio at the specified conditions. Select an air-fuel ratio of 34.2 (stoichiometric) and determine the appropriate NOX in grams per brake horsepower hour as related to the 100% air flow curve. Next go to Figure 18A which specifies the range of power outputs in percent maximum BMEP at any air-fuel ratio for specified conditions. Selecting the 100% air flow curve at stoichiometric air-fuel, determine the percentage of maximum load. Repeating this procedure for all other possible combinations, each endpoint for the 7° timing of Figure 16A can be determined. Similarly, data for the advanced (20°) and retarded (0°) ignition timings shown on Figure 16A were taken from the plots of experimental data shown in Figures 30A through 31E for the advanced combination angle and in Figures 32A through 33E for the retarded combination angle.

Figure 19 gives additional emission characteristics when NOX is plotted on a parts per million basis for the intermediate combination angle. Figures 20A through 20C give emission characteristics as they relate to engine power. Figure 21 relates exhaust gas temperature to NOX emission for all tests.

B. Low Power Experimental Data

Figures 22A and 22B present the various emission and power characteristics obtained with the engine operating at reduced loads and in the lean fuel region. Table 4 lists the data recorded for these low power experiments. Engine operation was as previously described and the data taken were according to the format of Figure 14.

C. Discussion

It will be noted that the power-speed plot (Figure 12) for this engine as modified resulted in a smooth curvalinear relationship. Recall, however, that the general trend and peak for this curve was arbitrarily established.

That is, fuel was forced into the engine until the desired power output was obtained. When this circumstance is considered in the interpretation of the BMEP air-fuel plots such as Figure 18A, an explanation for the behavior of the 80% and 100% relative air curves (as compared to the 70% air curve) is needed. As previously mentioned, it is hypothesized that localized cylinder heating resulted in the formation of a hot spot in the area of the exhaust valve. This hot spot could cause an elongation of the exhaust valve such that compression (and consequently power) loss, as well as oil consumption, would occur. This power drop would in turn require more fuel in order to force the power output to match the value shown by the curve of Figure 12. The fuel increase in turn would cause the 70% air curve of Figure 18A to be skewed to the left and downward.

Actually this phenomena was observed in the low power-lean fuel tests. Therein at power levels that resulted in exhaust gas temperatures above about 1150°F. a marked power drop was observed from the time of cold start until steady state operation was attained. This drop in power was not observed to occur at cooler exhaust temperatures. Roughly, this value of exhaust gas temperature corresponds to all power level values above the 3,000 RPM, 35% maximum power condition. Assuming this analysis to be correct, lower temperature operation such as could be achieved with a water-cooled engine modification, should yield a smooth family of increasing power curves with increasing relative air percent. The expected decreased fuel requirements accompanying this modification (i.e. that required to drive the engine to the same power level) would in turn decrease the emissions on a grams NOX per brake horsepower basis. Efficiency and other fuel related terms would also be improved.

As expected, Figure 21 indicates that no particular relationship exists between exhaust gas temperature and NOX emission. In general, an increase in exhaust gas temperature will indicate an increase in NOX. However, other factors, such as combination angle, strongly influence the trend so that no general correlations can be made.

No matter how one judges the hydrogen engine emission characteristics, whether on a parts per million or a grams per brake horsepower hour basis, the results remain that the NOX emission is many times less than reported for internal combustion engines using normal hydrocarbon fuels. On a ppm basis, the hydrogen engine has been found by this study to have between five and fourteen times less peak NOX emission when compared to the referenced engines of Figure 23. On a gram basis again the hydrogen engine yields about three times less peak emission than the gasoline counterpart (see Figure 24). Note that the gasoline data of Figure 24 represents emission values as related to indicated horsepower while the hydrogen data is related to brake horsepower. If the gasoline data were to be plotted relative to brake horsepower, their NOX emission would be increased by a factor of 3 assuming a 33 1/3% mechanical efficiency. Then the peak hydrogen emission would be about nine times less than its hydrocarbon counterparts.

The fact that this hydrogen engine yields less NOX emission than gasoline engines should be considered a basic characteristic of the hydrogen engine.

This advantage, however, should in no way be construed to be the minimum NOX emission which can be achieved with hydrogen engines in general. This statement is based on the fact that very little effort has been made to reduce the NOX emitted from this engine.

Comprehensive exhaust gas analyses were performed at the low power WOT tests for each of the five engine speeds. Exhaust gas samples were collected in liter bottles (under vacuum) directly after being cooled and before passing through the dryers of the exhaust sampling system of Figure 5A. The samples were analyzed by Phillips Petroleum Company. The resulting data are presented in Table 5. The data from this analysis supports the hypothesis that the hot spot which had caused compression loss was associated with a significant oil consumption. (The measured hydrocarbon concentrations are not large but the fact that any significantly measurable quantities exist in the exhaust of a hydrogen engine is a matter needing explanation.)

VIII. SECOND PHASE ENGINE MODIFICATION AND TESTING

A. Engine Modification

A decision to add a water jacket to the hydrogen engine was made during the final phase of this research effort. This modification (see Figure 25) consisted of the design and fabrication of a shell encircling the cooling fins of the cylinder. Fresh water was admitted intermittently through a water control valve and flexible plastic tubing. Heat transfer was facilitated by boiling the water within the jacket and venting the resultant steam through a stand-pipe located near the top of the water jacket. Cylinder head cooling was achieved by spraying water onto the cooling fins.

B. General

Water cooling considerably improved the heat transfer characteristics of this engine to the point that long-duration high-power test runs without head gasket deterioration or power loss due to compression leaks at localized hot spots was possible for the first time. As will be shown later, oil consumption was reduced to a negligible quantity. The cylinder wall near the exhaust valve which formerly had been operating hot was now operating at a much lower temperature.

C. Water Cooled Engine Tests and Data

Remaining time and funds were sufficient for only limited additional engine testing. The combination angle of ($+35^{o}$, X, -35^{o}) was selected for water cooled engine operation. For these tests, X represented a variable spark ignition angle determined for each run for best power without knock.

During the 39 water jacketed runs for which data were taken, this angle varied between +15 and -4 degrees. Figure 26 illustrates the variables tested during the water jacketed engine runs. Basically, this is a repeat of runs made for the intermediate combination angle of Figure 10. For these tests, fuel was injected until the flow rate matched the flow rate used in the non-water jacketed first phase tests. Power output, oxides of nitrogen and values for other variables recorded are presented in Table 6.

Liter bottle exhaust samples were taken for selected data points. These bottles were delivered to Phillips Petroleum Company Research Laboratory for chromatographic analysis. The results of this analysis are tabulated in Table 7.

D. Discussion and Data Graphics

As expected, the water jacketed engine overcame the power losses associated with high power, high temperature, air cooled runs. An examination of Figures 27A through 27E illustrates the expected smooth drop in power level with reduced throttle. In contrast, Figures 18A through 18E show an increase in power at some reduced throttle conditions. The resulting predictable behavior of the water jacketed engine data indicates that it is a more reliable indicator of this engine's true characteristics than is the above reported air-cooled data. (Figure 27F is a composite plot of the data presented in Figures 27A -27E.)

Figures 28A through 28E and the accompanying scatterplot of Figure 28F provide output for the crossplot needed to convert the data to the form required by the sponsor. The resulting tree diagram (see Figures 29A through 29E) is the water jacketed data presented in this desired format.

Similar graphs showing engine emissions as a function of air-fuel ratio for various throttle settings with the engine timed at 20°BTC are presented in Figures 30A through 30E for the range in engine speed from 2000 RPM to 4000 RPM. Figures 31A through 31E present the performance characteristics of the engine for this ignition timing. Finally, Figures 32A through 32E present the emissions as a function of air fuel ratio, air flow, and engine speed for the ignition timing of 0° BTC. Figures 33A through 33E present the associated engine performance data for these tests.

IX. GASOLINE TESTS

A set of five gasoline fueled engine tests were made for a final comparative evaluation. The water jacketed engine was used for these tests. To facilitate the fuel change, the throttle tube was replaced by a standard Clinton carburetor and the hydrogen injection tube was plugged. All runs were taken at wide-open-throttle, best power mixture (rich), and best power ignition timing.

Table 8 lists the observed and calculated data for this test sequence. The data for run 757 shows an unexpected low value for fuel flow which is probably erroneous. (It is believed that the actual fuel flow was incorrectly recorded for this run. Unfortunately, no time was available to make confirming runs.) Note that maximum gasoline power proved to be almost identical to the predicted value of maximum power used in initial hydrogen design calculations.

Chromatographic analyses of liter bottle exhaust samples for all runs was made by Phillips Petroleum Research Laboratory. The results of those analyses are presented in Table 9.

X. COMPARISON OF EMISSIONS

The data in Tables 5 and 7 show that components other than combustion water and the constituents of air were present in the exhaust of the hydrogen fueled engine. The emissions in this case reflect a) the two phases of hydrogen engine evolution represented by data contained within each Table, b) the specific design used in each phase of the project effort, and c) the experimental operating conditions.

As previously described, the first phase engine tests were made with an "air-cooled" version whose exhaust contained significant concentrations of carbon monoxide and unburned hydrocarbons. The concentration of these components was found to increase with engine loading as shown by the data presented in Figures 34 and 35. Leakage of lubricating oil past the intake valve stem and into the combustion chamber was the primary source of these pollutants. This condition was corrected in the second phase "water-cooled" engine by insertion of an oil seal around the intake valve. The resulting decrease in hydrocarbon and carbon monoxide emissions is shown by comparison of the air-cooled and water-cooled curves of Figures 34 and 35.

Figure 35 also shows that the concentrations of unburned hydrogen in the exhaust decreases as engine power increases. The same trend may be noted for both the air-cooled and water-cooled engines. The presence of hydrogen in the exhaust is expected since stratified charge effects and position and intensity of the ignition source influence the reaction. Also the timing of the injection, ignition and exhaust mechanisms may individually or collectively prevent complete combustion of the hydrogen.

The expected emissions from a hydrogen fueled engine were steam, the constituents of air, and nitrogen oxides. If any lubricating oil was consumed in the process, the exhaust would also be expected to contain organic compounds, carbon monoxide and carbon dioxide. In addition, some unburned hydrogen may be present. All of these constituents were found to be present in the exhaust from the hydrogen engine. However, since carbonaceous compounds present were of minor concentration, or could be reduced to a minimal level by design changes which minimizes oil consumption, the only pollutants accorded significance are compounds of nitrogen.

Comprehensive analyses for nitric oxide (NO) produced by the experimental engine as a function of engine speed, throttle setting and loading were conducted simultaneously with the engine performance tests. (The measuring apparatus was arranged so that the exhaust would be analyzed within 20 seconds after it left the combustion chamber. Under these conditions it appears reasonable that very little of the primary oxide would be oxidized to the dioxide. Accordingly, it was assumed the NO measured represented the total NOX.) Nitrogen oxide emissions were then normalized to account for differences in engine output and expressed as grams NOX/brake horsepower-hour.

The inter-relationship of emissions and performance for the air-cooled experimental hydrogen engine is summarized in Figure 36. A similar graph of the experimental data for the water-cooled version of this same engine is presented in Figure 37. It will be noticed in both cases that NOX emissions generally increase with an increase in torque (% Max. BMEP). The maximum NOX produced is 3.0 grams/BHP-Hr with 2.0 grams/BHP-Hr being about average for all levels of engine performance. If the engine were operated at 35% power or less, as is frequently the case for automobile engines, the NOX would average about 1.0 grams/BHP-Hr. If the NOX emissions were expressed on the basis of "indicated" horsepower, and the engine had a 33 1/3% mechanical efficiency, the NOX at less than 35% power would average about 0.33 grams/IHP-Hr. On this basis, the NOX emissions from the hydrogen engine were about nine times less than would be expected from a gasoline engine.

XI. CONCLUSIONS

The work performed under this contract has yielded much information about design criteria for hydrogen fueled internal combustion engines.

In the first place, it has been shown that a conventional gasoline fueled engine can be readily converted to hydrogen operation. The specific design approach utilized was unique in that it eliminated problems of pre-ignition and detonation which had plagued prior workers in this field.* Successful engine operation was obtained with spark, hot wire and compression ignition. The engine was easy to start and ran smoothly over the range in fuel from very rich to very lean. It should be noted that the engine's operating temperature with hydrogen fuel was comparable to that obtained with gasoline operation under similar operating conditions.

Secondly, hydrogen engine performance has been achieved which could match or exceed that obtainable with gasoline operation as desired. This freedom in engine operation was possible at all engine speeds because of the wide flammability limits for hydrogen which allowed fuel injection to exceed that necessary to match the gasoline engine's power output. For purposes of comparison, the maximum brake mean effective pressure of 75.4 psi at 3000 RPM was considered although the engine was capable of being driven to higher BMEP values. The brake specific fuel consumption under varying loads was always less than 0.5 pounds of hydrogen per brake horsepower hour.

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* Smooth combustion is made possible only by the design used in this engine. This claim cannot be made by other designs reported in the literature. Accordingly, all claims for a hydrogen-fueled engine made herein cannot be unilaterally applied to other engine designs.

Thirdly, in support of expected results, the emissions from a hydrogen engine were found to contain only trace to negligible concentrations of carbon monoxide and other organic compounds normally associated with the exhausts of gasoline engines. In addition, there should be no undesirable sulfur or lead compounds in the exhaust. The only pollutant found to be present in significant quantity was nitric oxide. Its concentration averaged about nine times less than the NOX emissions typically reported for internal combustion engines burning conventional hydrocarbon fuels.

A total of 48-3/4 hours of intermittant hydrogen engine operation without accident has been accumulated in the course of this work.

It appears from the research that a multi-cylinder hydrogen fueled engine could be constructed which would meet the 1975/76 vehicle emission standards.

XII. RECOMMENDATIONS

This project was undertaken to determine if an engine run on hydrogen could give satisfactory operation without the undesirable pollutants produced by gasoline engines. It is believed the project has been very successful in that the potential of hydrogen as a low polluting fuel has been demonstrated.

Further efforts to improve the engine's performance or to establish additional design criteria for other engines appear to be worthwhile and are highly recommended. At the same time, consideration should be given to the development of fuel storage and distribution systems. The use of more optimal compression ratios in multi-cylinder engine applications should also be considered.

XIII. CALCULATIONS

The following are the equations and relationships used to compute the tabulated data.

$$P = \frac{FNC_1}{10,000} \qquad (1)$$

$$\dot{M}_a = AC_1 \qquad (2)$$

$$\% P_{max} = \frac{100P}{P_{max}} \qquad (3)$$

$$T = \frac{5250\ P}{N} \qquad (4)$$

gasoline runs only $$\dot{M}_g = \frac{W_g}{\gamma} \qquad (5A)$$

hydrogen runs only $$\dot{M}_H = 0.309\ Q_H \quad \text{for } Q_H \leq 1.3 \qquad (5B)$$

hydrogen runs only $$\dot{M}_H = 0.542\ Q_H - 0.314 \quad \text{for } Q_H > 1.3 \qquad (5C)$$

$$A/F = \frac{\dot{M}_a}{\dot{M}_x} \qquad (6)$$

$$E = \frac{254500\ P}{M_x H} \qquad (7)$$

$$\% SA = \frac{100(A/F)}{S} \qquad (8)$$

$$\text{BSFC} = \frac{\dot{M}_x}{P} \tag{9}$$

for rich gasoline mixture only

$$\dot{N}_E = 8 + \frac{3.773}{4.773}\,\frac{A}{F}\,\frac{116}{28.9}\,\frac{\dot{M}_g}{116} \tag{10A}$$

for lean gasoline mixture only

$$\dot{N}_E = \frac{A}{F}\,\frac{116}{28.9} - 4.5\,\frac{\dot{M}_g}{116} \tag{10B}$$

for rich hydrogen mixture only

$$\dot{N}_E = 1 + \frac{1.773}{4.773}\,\frac{A}{F}\,\frac{2}{28.9},\frac{\dot{M}_H}{2} \tag{10C}$$

for lean hydrogen mixture only

$$\dot{N}_E = \frac{A}{F}\,\frac{2}{28.9} - 0.5\ \ \dot{M}_H \tag{10D}$$

$$M_N = \frac{(453.6 \times 10^{-6})\,(NOX)\,(\dot{N}_E)\,\Phi_{NO}}{P} \tag{11}$$

$$\dot{Q}_t = \frac{30\ N(PD)}{1728} \tag{12}$$

$$\dot{M}_{at} = \frac{144\ \dot{Q}_t\ (0.491)\ (P_b - P_a)}{53.35\ \theta} \tag{13}$$

$$\%\ TH = 100\ \frac{\dot{M}_a}{\dot{M}_{at}} \tag{14}$$

$$\text{BMEP} = \frac{2545\ P\ 778}{144\ \dot{Q}_t} \tag{15}$$

$$\%\ B_{max} = \frac{100\ \text{BMEP}}{75.4} \tag{16}$$

XIV. NOMENCLATURE

P = brake horsepower

F = dynamometer force - pounds

N = engine speed -RPM

C_1 = pressure, temperature, and humidity correction factors taken from dynamometer manufacturers curves

$\dot{M}_a$ = air flow - pounds per hour

A = uncorrected air flow reading

P_{max} = maximum horsepower

$\%P_{max}$ = percent of maximum horsepower

T = torque - foot pounds

$\dot{M}_g$ = gasoline flow - pounds per hour

W_g = weight of gasoline - pounds

γ = time - hours

$\dot{M}_H$ = hydrogen flow - pounds per hour

Q_H = meter reading - standard C. F. M.

A/F = air-fuel ratio

$\dot{M}_x$ = appropriate fuel flow - M_g or M_H

E = overall brake thermal efficiency - percent

H = lower heating value of fuel - 51, 100 for hydrogen or 19, 000 for gasoline

%SA = percent stoichiometric air

S = stoichiometric air-fuel ratio - 34. 2 for hydrogen or 15 for gasoline

BSFC = brake specific fuel consumption - pounds per horsepower hour

M_N = nitric oxide mass emission - grams per horsepower hour

NOX = nitric oxide concentration - parts per million

$\dot{N}_E$ = mole rate of flow of exhaust - pound moles per hour per mole fuel

Φ_{NO} = molecular weight of nitric oxide - 30

$\dot{Q}_t$ = theoretical piston displacement - cubic feet per hour

PD = piston displacement per cycle - cubic inches

$\dot{M}_{at}$ = theoretical air mass rate of flow - pounds per hour

P_b = barametric pressure - inches of mercury

P_a = air meter pressure drop - inches of mercury

θ = dry bulb temperature - degrees Rankine

%TH = percent throttle

BMEP = brake mean effective pressure -psi

$\%B_{max}$ = percent maximum BMEP

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3. Deen, J. L. and Schoeppel, R. J., "Hydrogen and the Electric Economy," Proceedings, Frontiers of Power Technology Conference, Oklahoma State University, Stillwater, Oklahoma, September 30-October 1, 1971, p. 10-1.

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6. Murray, R. G., and Schoeppel, R. J., "A Reliable Solution to the Environmental Problem: The Hydrogen Engine," Paper 700608, presented at SAE/AIAA/ASME Reliability and Maintainability Conference, Detroit, (July 20-22, 1970).

7. Schoeppel, R. J., and Sadiq, S., "The Role of the Power Industry in Supporting the Hydrogen Engine and Clean Air," Proceedings, Frontiers of Power Technology Conference, Stillwater, Oklahoma (October 15-16, 1970).

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10. Schoeppel, R. J., and Murray, R. G., "The Development of Hydrogen Burning Engines." Proceedings, Frontiers of Power Technology Conference, Oklahoma State University (1968), p. 12.

11. Wimmer, D. B. and McReynolds, L. A., "Nitrogen Oxides and Engine Combustion, "SAE Transactions," Vol. 70, 1962.

12. Fleming, R. D. and Allsup, J. R., "Propane as a Fuel for Clean Air Requirements, Part 1." Paper presented at L-P Gas Engine Fuel Symposium, Detroit (October 21-22, 1970).

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14. Lichty, L. C., Combustion Engine Processes, McGraw-Hill, N. Y. p. 208 (1967).

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Expected Emissions

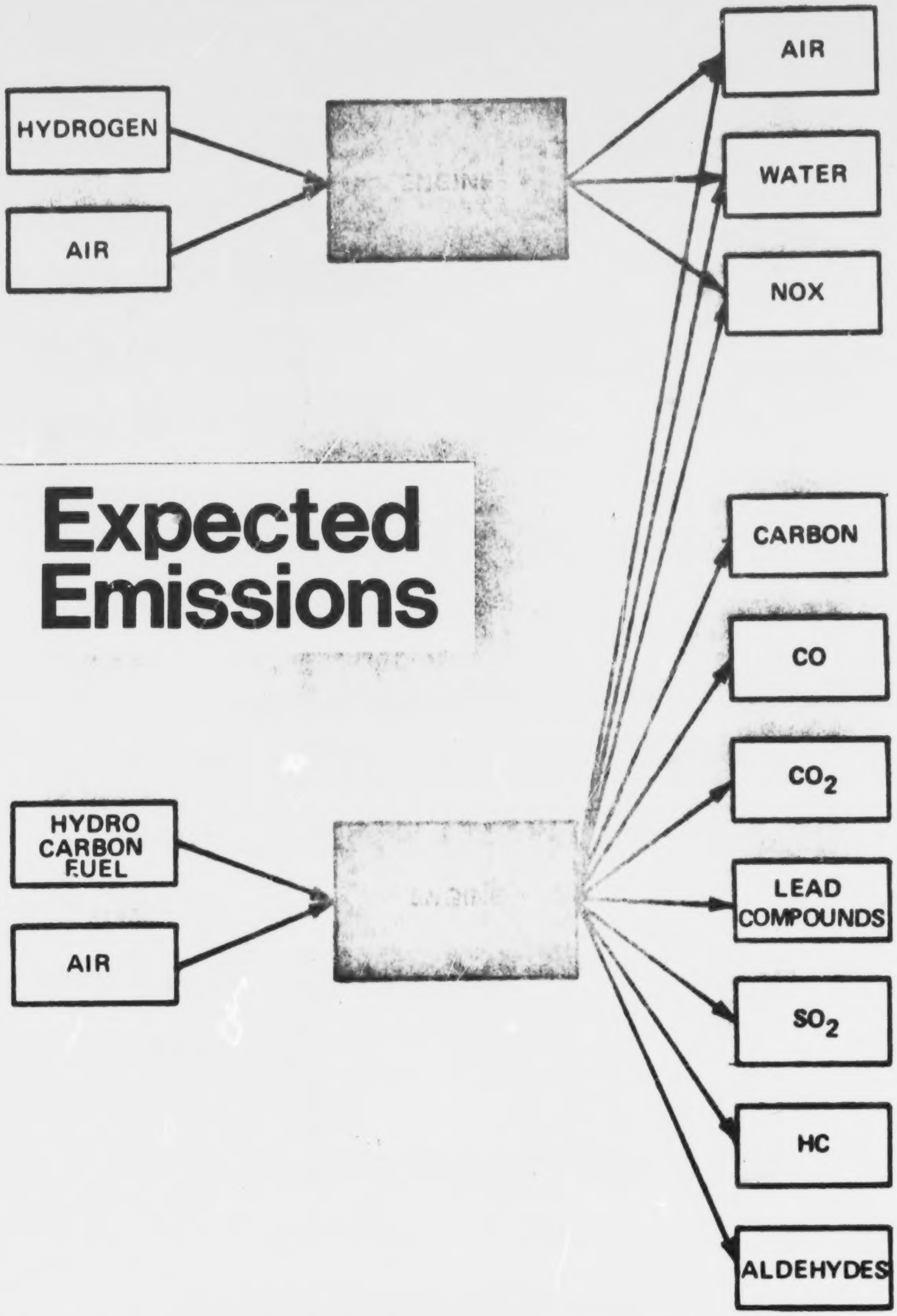

HYDROGEN
AIR
ENGINE
AIR
WATER
NOX
HYDRO CARBON FUEL
AIR
ENGINE
CARBON
CO
CO_2
LEAD COMPOUNDS
SO_2
HC
ALDEHYDES

FIGURE 1 FUEL–ENGINE SYSTEM EMISSIONS

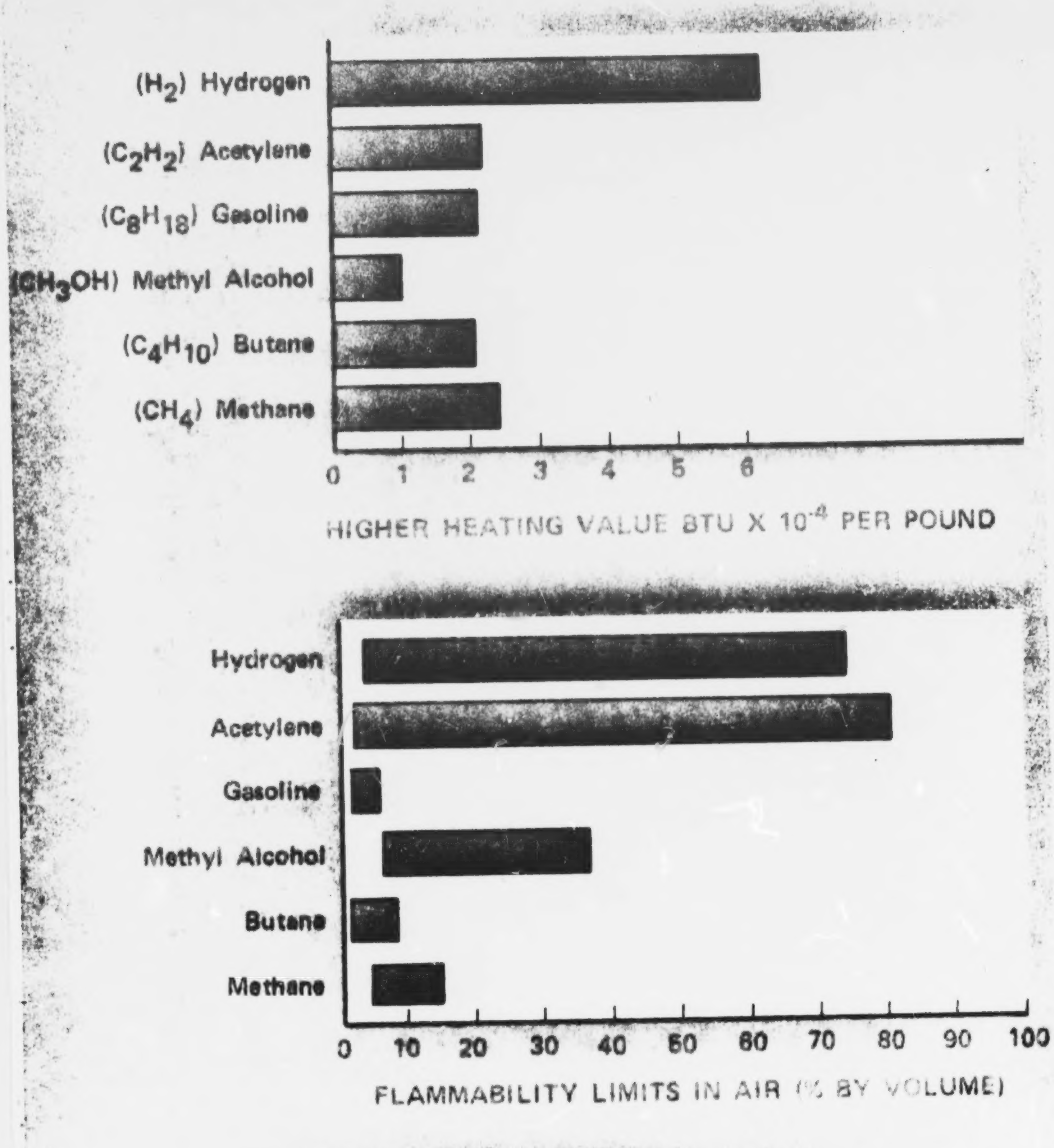


FIGURE 2 - FUEL CHARACTERISTICS FROM REF. 13-15

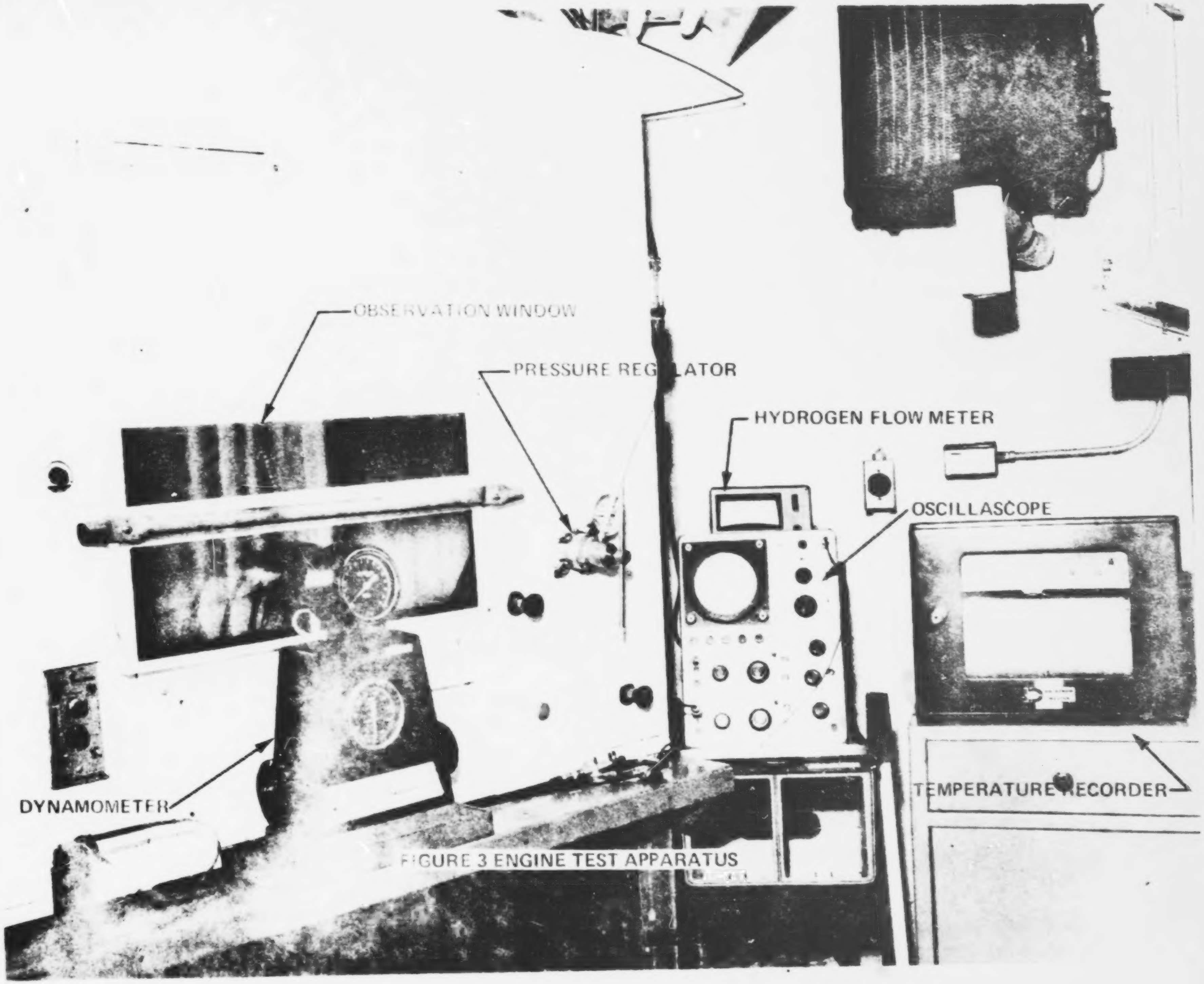

OBSERVATION WINDOW
PRESSURE REGULATOR
HYDROGEN FLOW METER
OSCILLASCOPE
DYNAMOMETER
TEMPERATURE RECORDER

FIGURE 3 ENGINE TEST APPARATUS

NOT REPRODUCIBLE

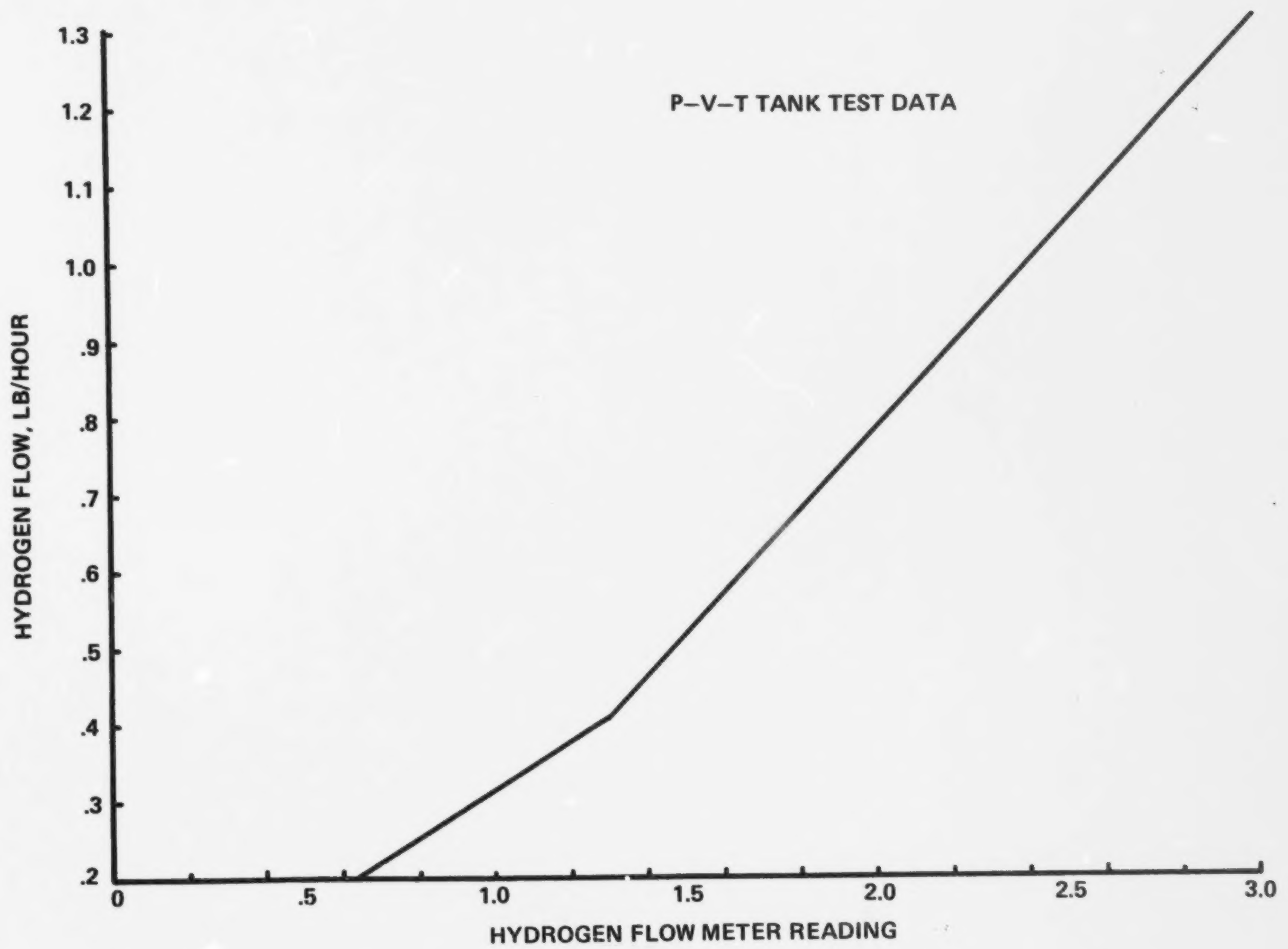


FIGURE 4 FUEL FLOWMETER CALIBRATION CURVE

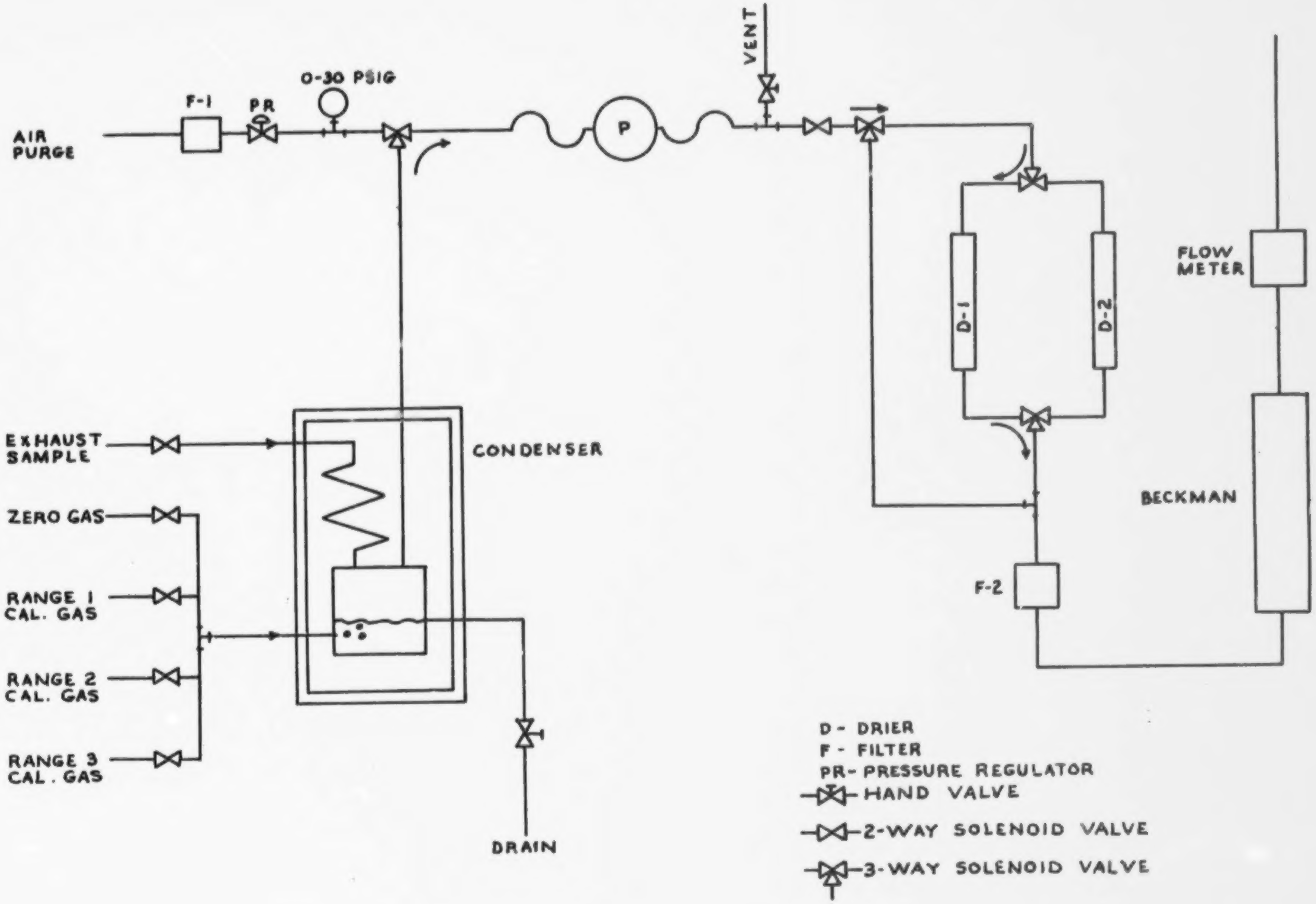

AIR PURGE
F-1
PR
0-30 PSIG
P
VENT
EXHAUST SAMPLE
ZERO GAS
RANGE 1 CAL. GAS
RANGE 2 CAL. GAS
RANGE 3 CAL. GAS
CONDENSER
DRAIN
D-1
D-2
F-2
FLOW METER
BECKMAN
D - DRIER
F - FILTER
PR- PRESSURE REGULATOR
HAND VALVE
2-WAY SOLENOID VALVE
3-WAY SOLENOID VALVE

FIGURE 5A NITRIC OXIDE SAMPLING SYSTEM SCHEMATIC

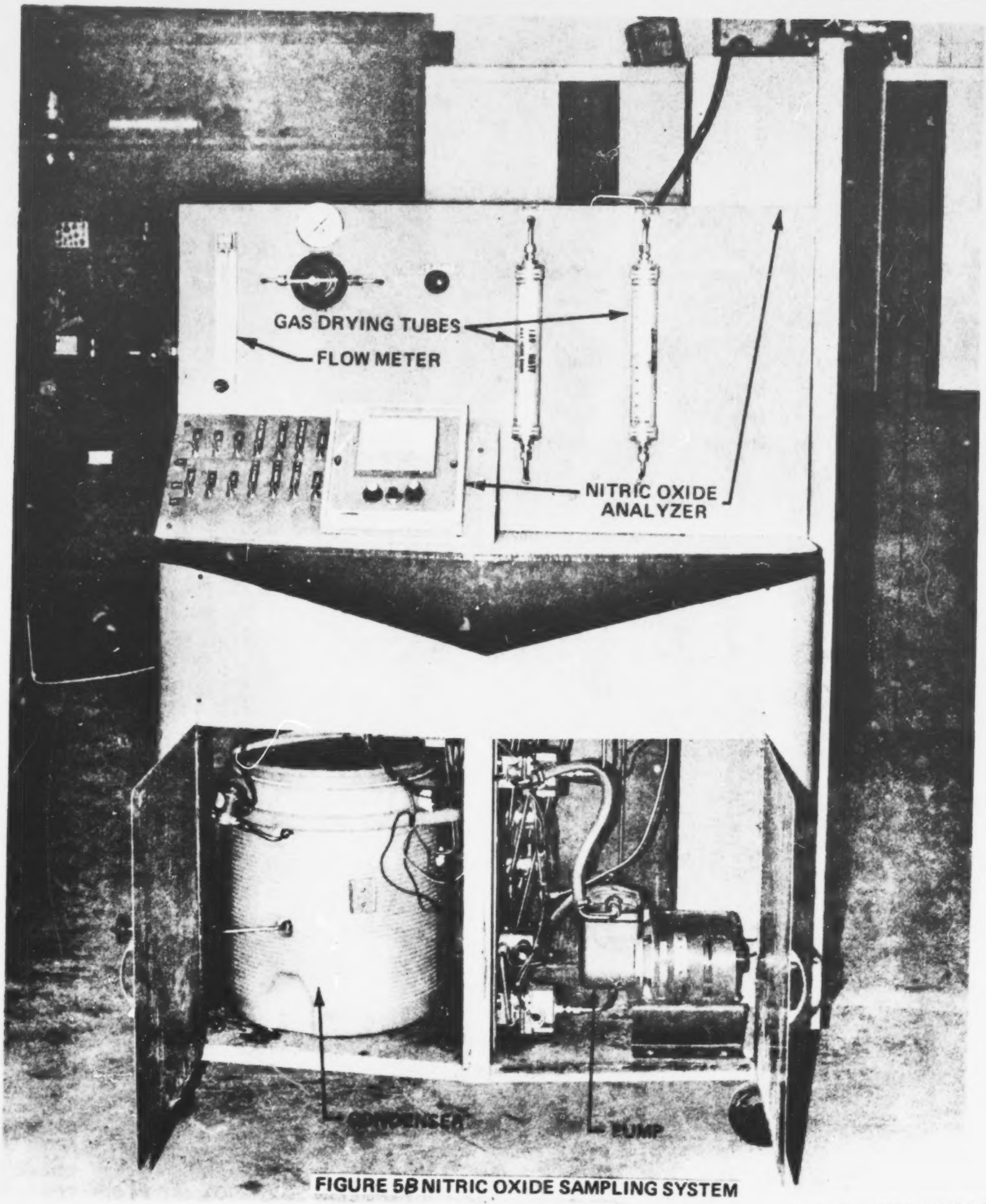

GAS DRYING TUBES
FLOW METER
NITRIC OXIDE ANALYZER
CONDENSER
PUMP

FIGURE 5B NITRIC OXIDE SAMPLING SYSTEM

NOT REPRODUCIBLE

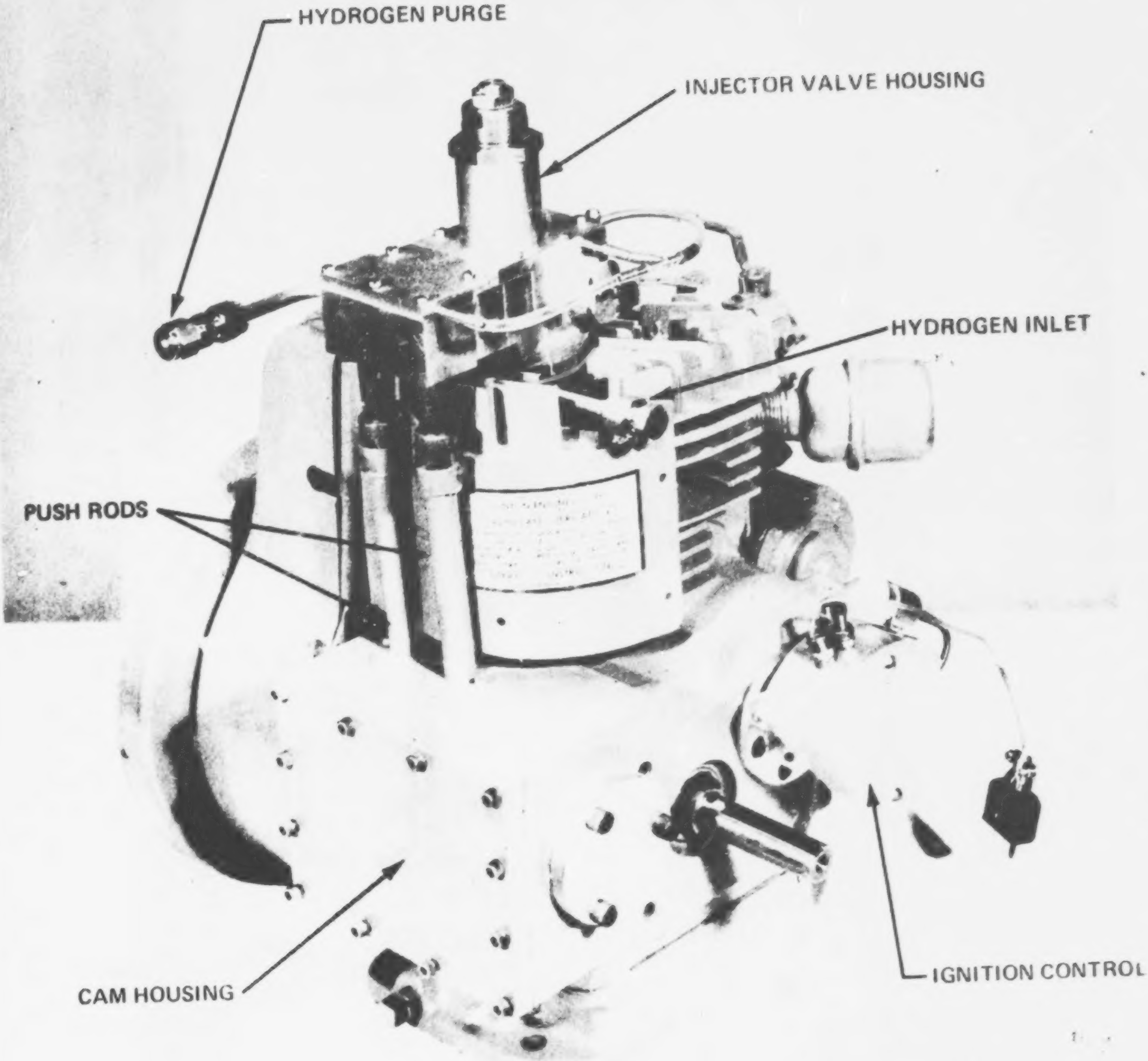

HYDROGEN PURGE
INJECTOR VALVE HOUSING
HYDROGEN INLET
PUSH RODS
CAM HOUSING
IGNITION CONTROL

FIGURE 6 HYDROGEN ENGINE–CAST IRON CRANK CASE

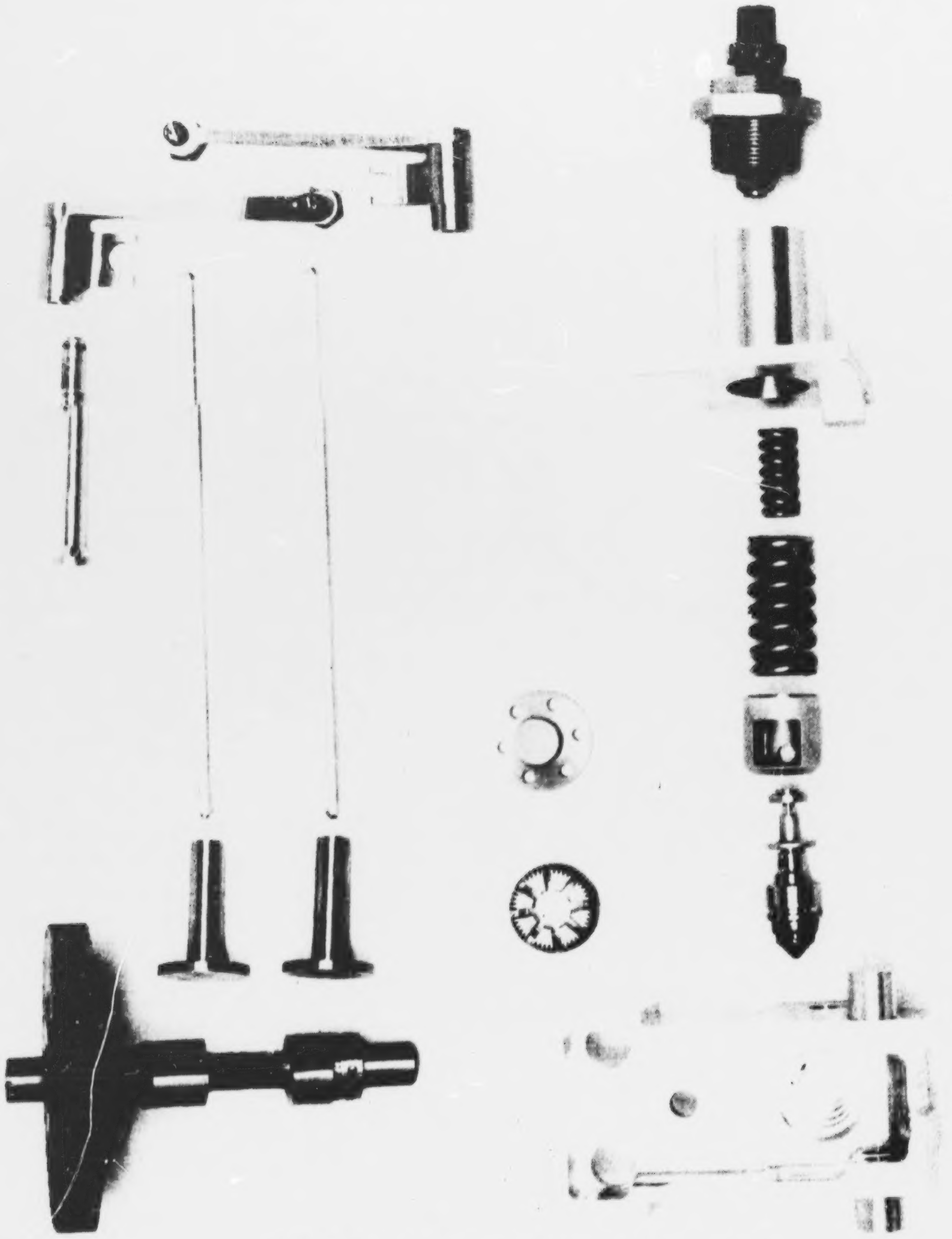


FIGURE 7 INJECTION MECHANISM COMPONENTS

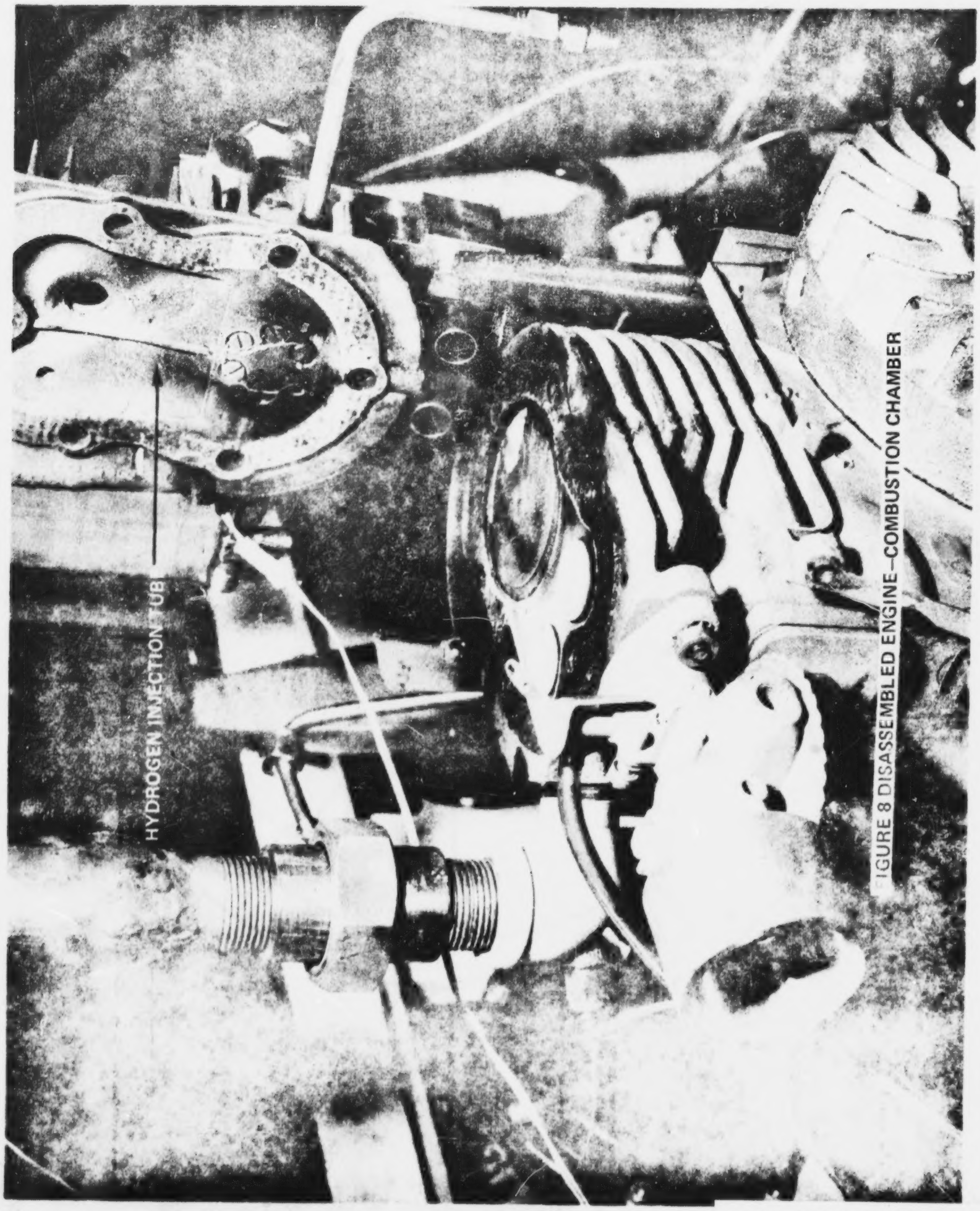

HYDROGEN INJECTION TUB

FIGURE 8 DISASSEMBLED ENGINE–COMBUSTION CHAMBER

NOT REPRODUCIBLE

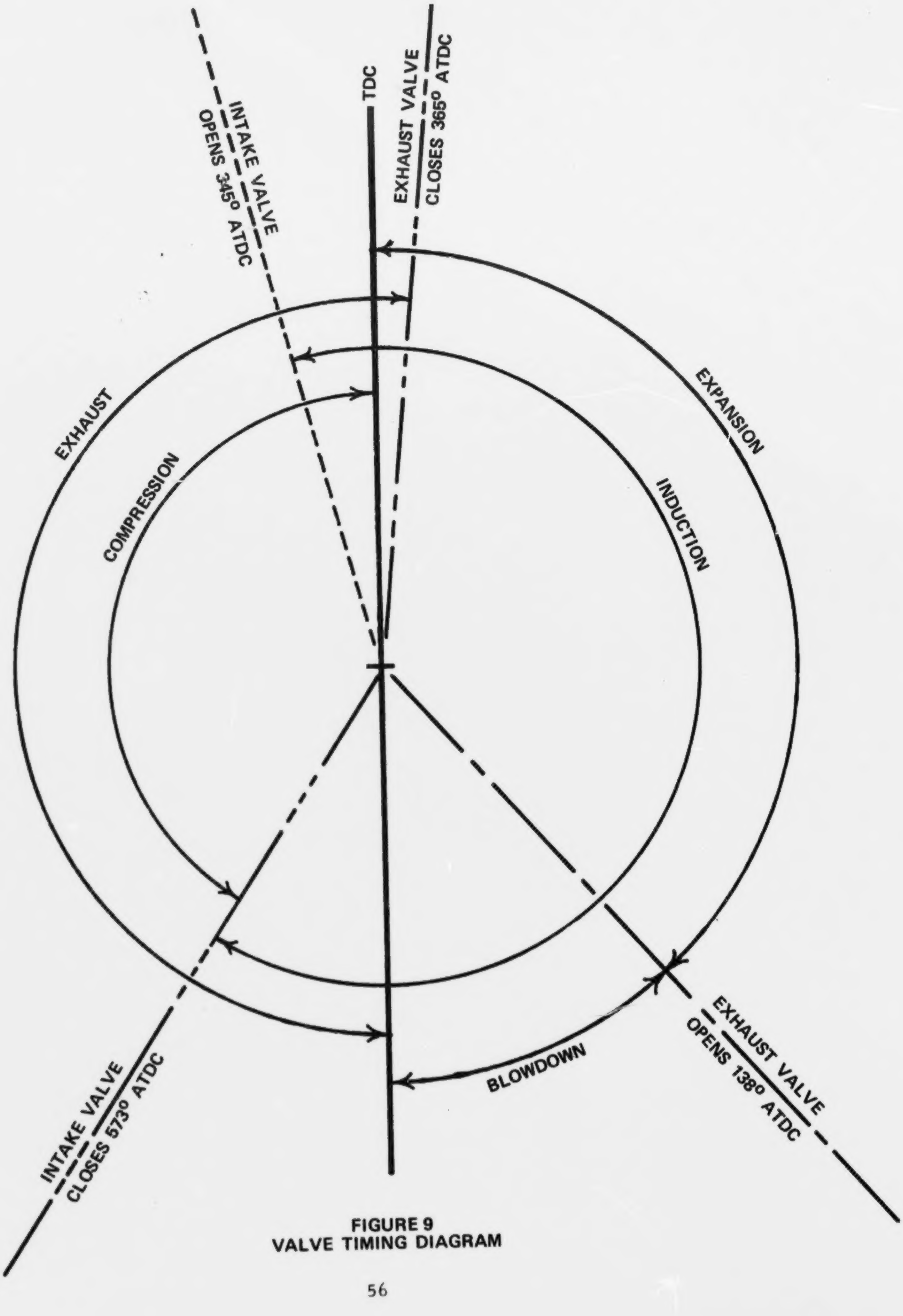
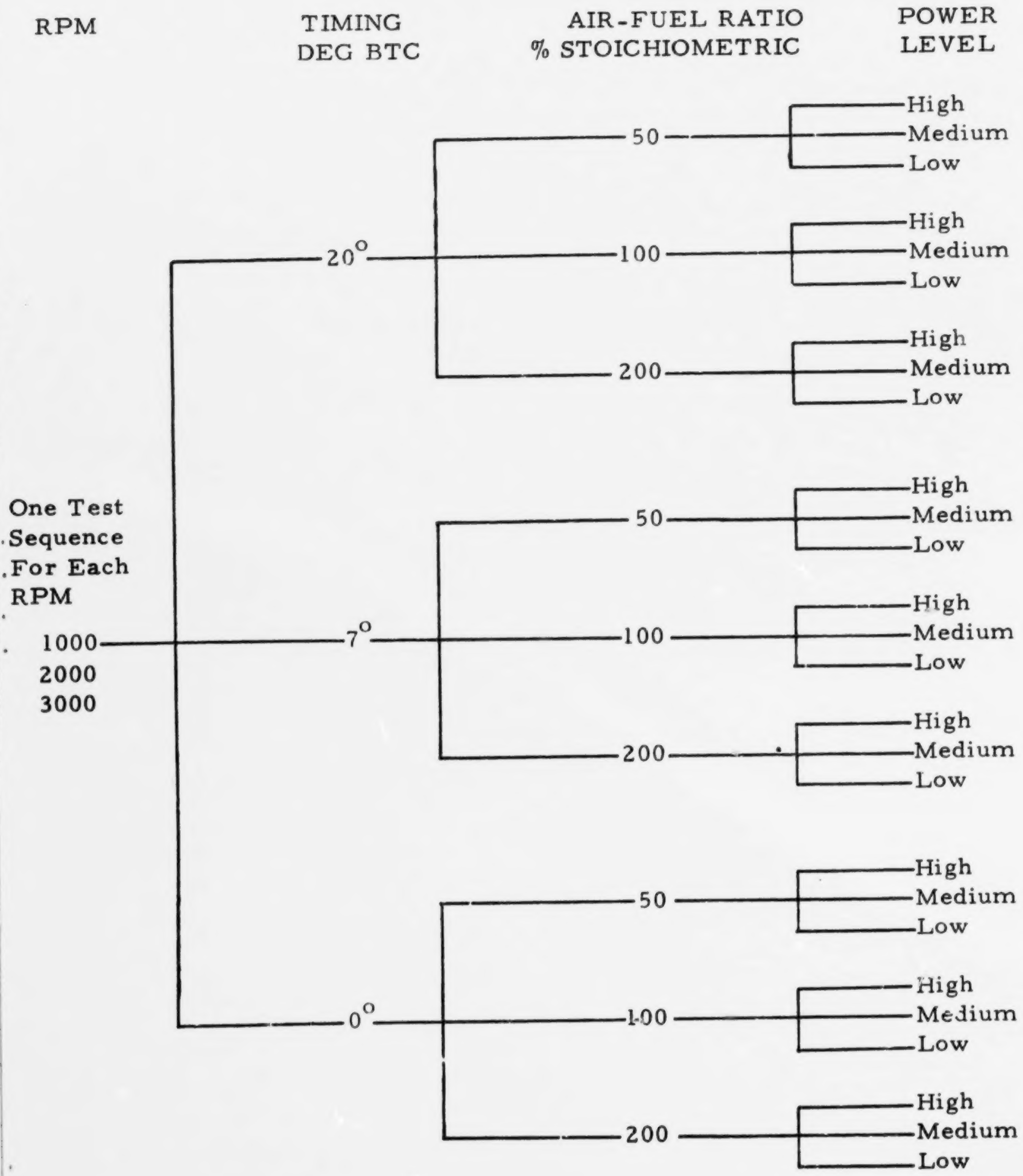

INTAKE VALVE
OPENS 345° ATDC
TDC
EXHAUST VALVE
CLOSES 365° ATDC
EXPANSION
EXHAUST
COMPRESSION
INDUCTION
BLOWDOWN
EXHAUST VALVE
OPENS 138° ATDC
INTAKE VALVE
CLOSES 573° ATDC

FIGURE 9
VALVE TIMING DIAGRAM

Figure 10

TREE DIAGRAM-- OAP DATA FORMAT


RPM
TIMING DEG BTC
AIR-FUEL RATIO % STOICHIOMETRIC
POWER LEVEL
One Test Sequence For Each RPM
1000
2000
3000
20°
7°
0°
50
100
200
High
Medium
Low

% MAX AIR FLOW	% MAX POWER	RPM	RUN NO. 20°BTC	RUN NO. 7°BTC	RUN NO. 0°BTC
100%	35%	2000	Misfire	Misfire	Misfire
		2500	630	563	Misfire
		3000	631	564	Misfire
		3500	632	565	Misfire
		4000	633	566	Misfire
	65%	2000	634	558	Misfire
		2500	635	557	601
		3000	636	556	602
		3500	637	555	603
		4000	638	554	604
	100%	2000	639	579	Misfire
		2500	640	577	605
		3000	641	560	606
		3500	642	559	607
		4000	643	578	608
80%	35%	2000	644	567	Misfire
		2500	645	568	Misfire
		3000	646	569	Misfire
		3500	647	570	Misfire
		4000	648	571	609
	65%	2000	649	572	610
		2500	650	573	611
		3000	651	574	612
		3500	652	575	613
		4000	653	576	614
	100%	2000	654	584	615
		2500	655	583	616
		3000	656	582	617
		3500	Misfire	581	618
		4000	657	580	619
70%	35%	2000	658	586	Misfire
		2500	659	587	Misfire
		3000	660	588	Misfire
		3500	661	589	Misfire
		4000	662	590	Misfire
	65%	2000	663	591	620
		2500	664	592	621
		3000	665	593	622
		3500	666	594	623
		4000	667	595	624
	100%	2000	668	596	625
		2500	669	597	626
		3000	Misfire	598	627
		3500	Misfire	599	628
		4000	670	600	629

Figure 11
TREE DIAGRAM--DATA RUNS--ADVANCED COMBINATION ANGLE

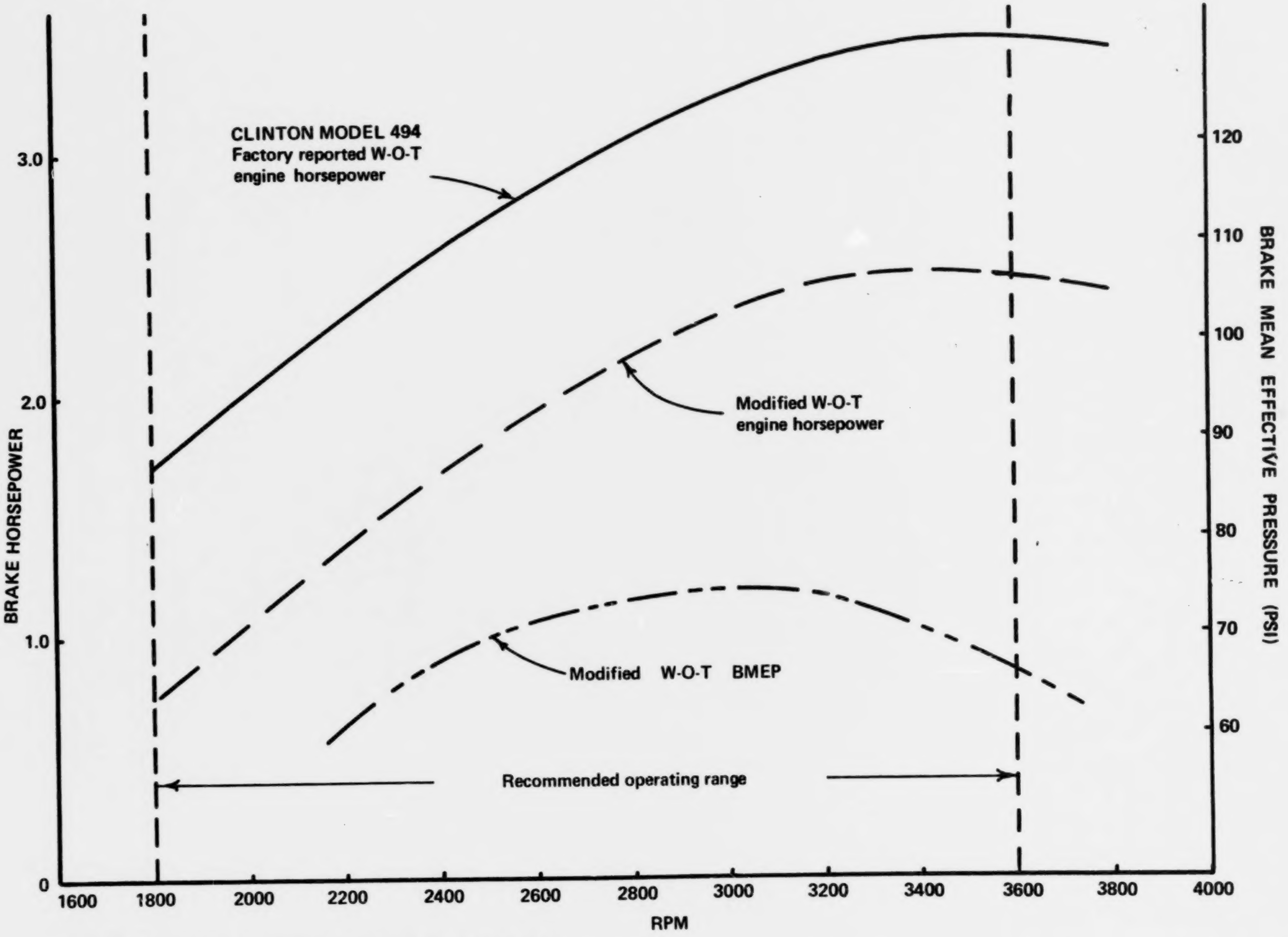
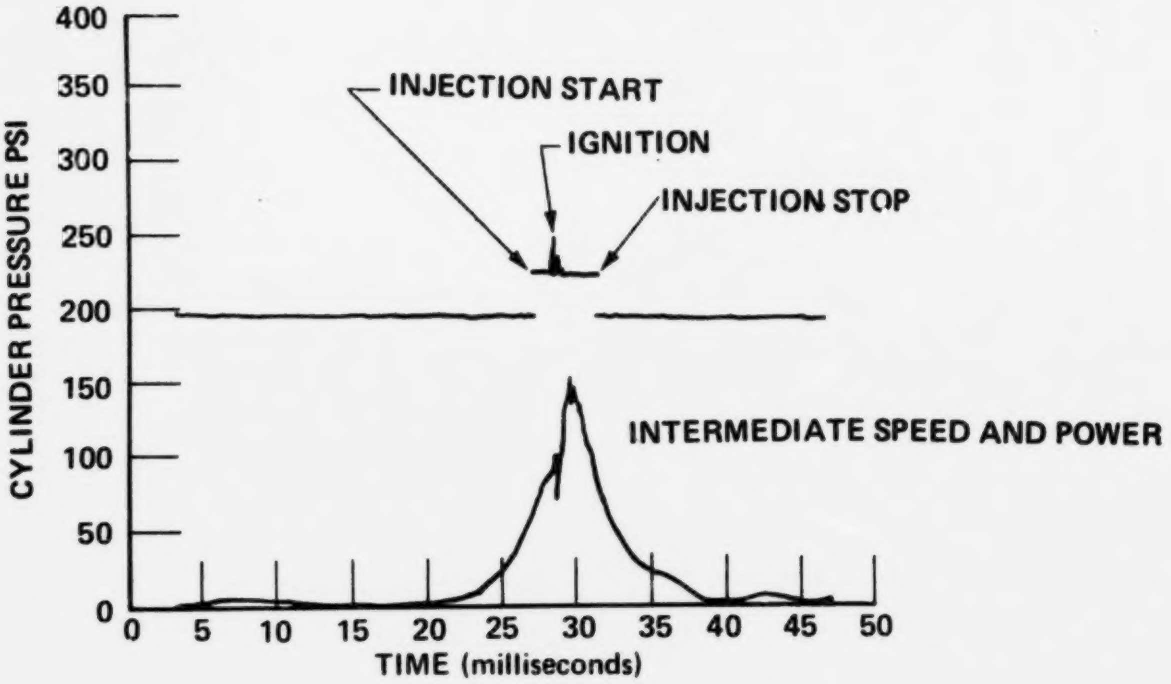


FIGURE 12 ENGINE PERFORMANCE CHARACTERISTICS



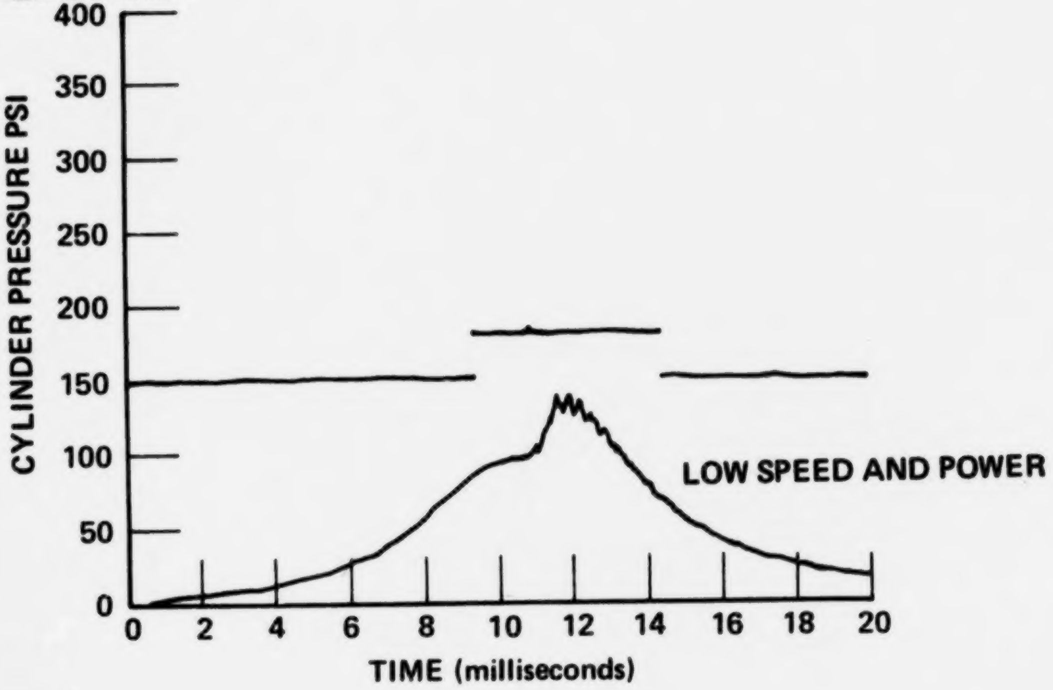


FIGURE 13A CYLINDER PRESSURE–TIME DIAGRAMS LOW AND INTERMEDIATE SPEED AND POWER

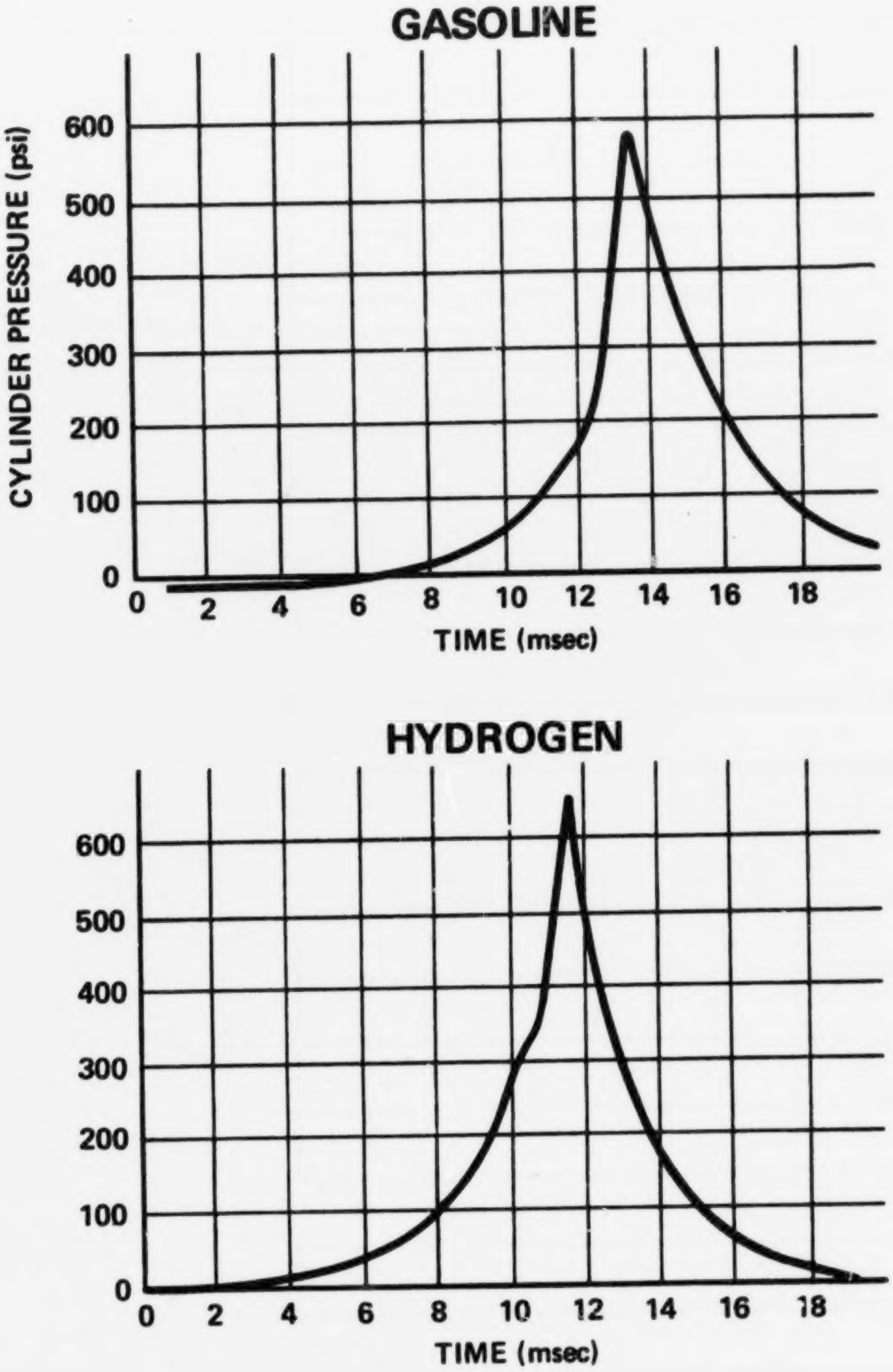
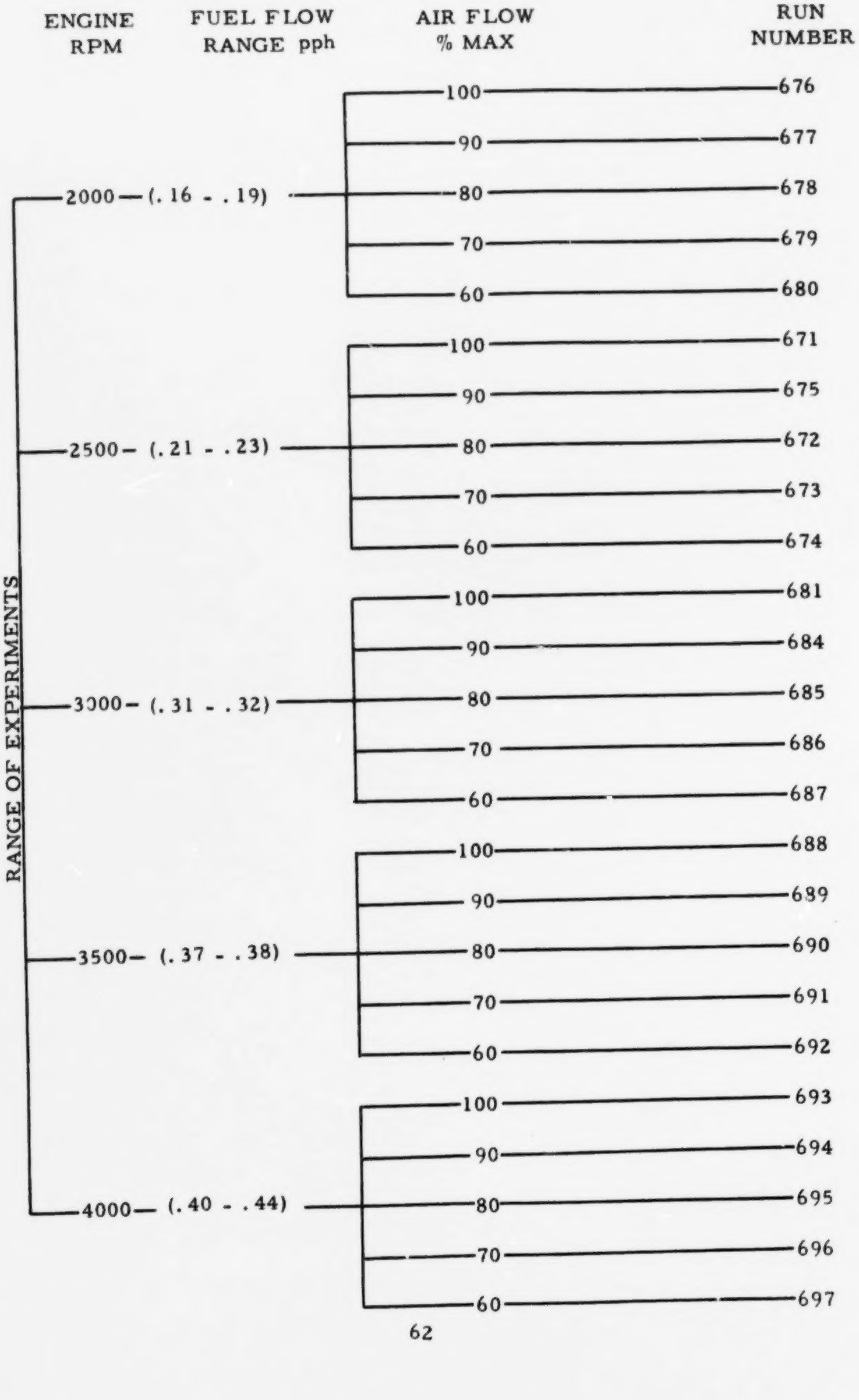


FIGURE 13B CYLINDER PRESSURE–TIME DIAGRAMS GASOLINE AND HYDROGEN OPERATION, INTERMEDIATE SPEED, HIGH POWER

Figure 14

TREE DIAGRAM OF LOW POWER, LEAN FUEL EXPERIMENTS


ENGINE RPM
FUEL FLOW RANGE pph
AIR FLOW % MAX
RUN NUMBER
RANGE OF EXPERIMENTS
2000 (.16 - .19)
100 676
90 677
80 678
70 679
60 680
2500 (.21 - .23)
100 671
90 675
80 672
70 673
60 674
3000 (.31 - .32)
100 681
90 684
80 685
70 686
60 687
3500 (.37 - .38)
100 688
90 689
80 690
70 691
60 692
4000 (.40 - .44)
100 693
90 694
80 695
70 696
60 697

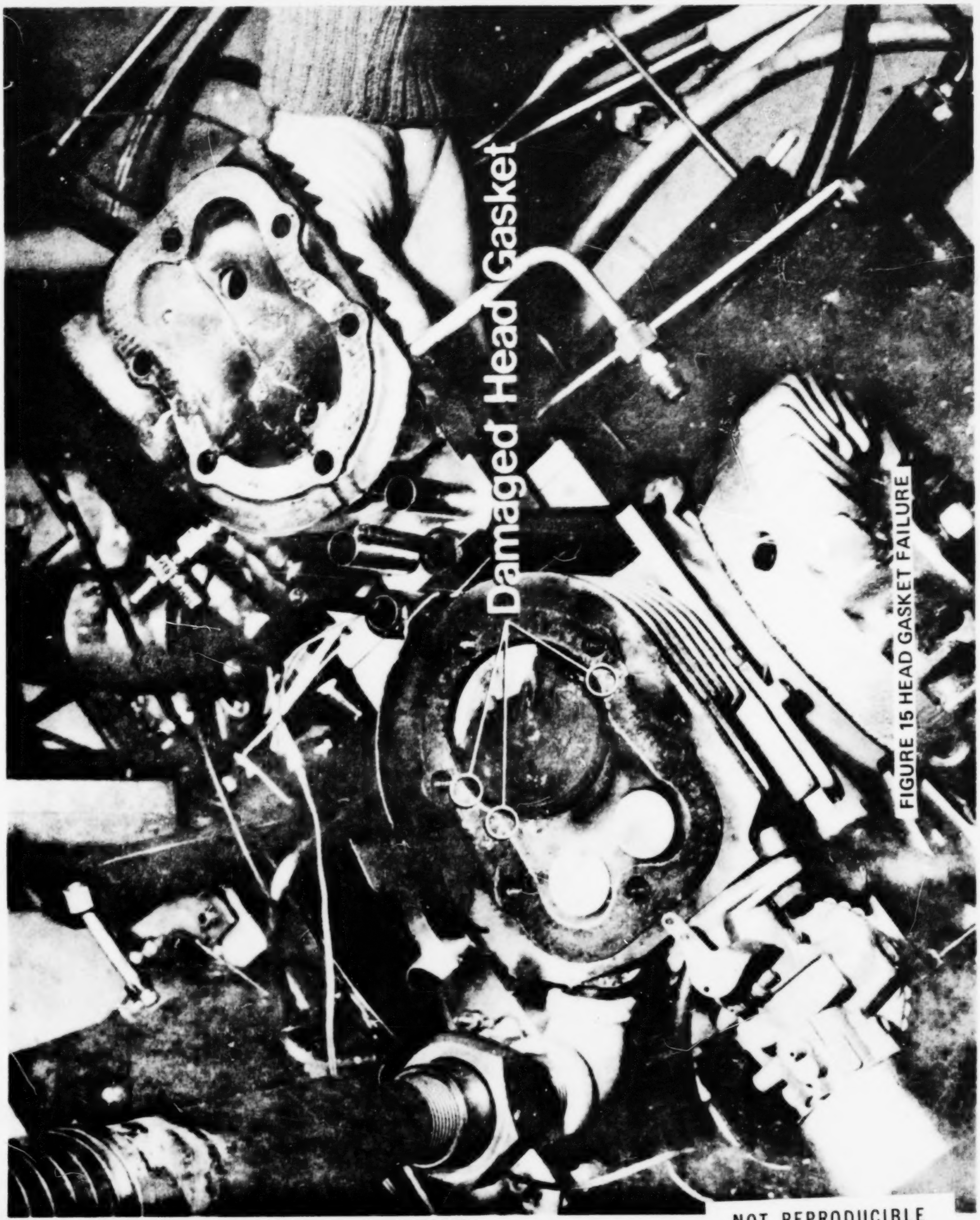

Damaged Head Gasket

FIGURE 15 HEAD GASKET FAILURE

NOT REPRODUCIBLE

Figure 16A

TREE DIAGRAM--OXIDES OF NITROGEN EMISSION-- OAP FORMAT
-2000 RPM-

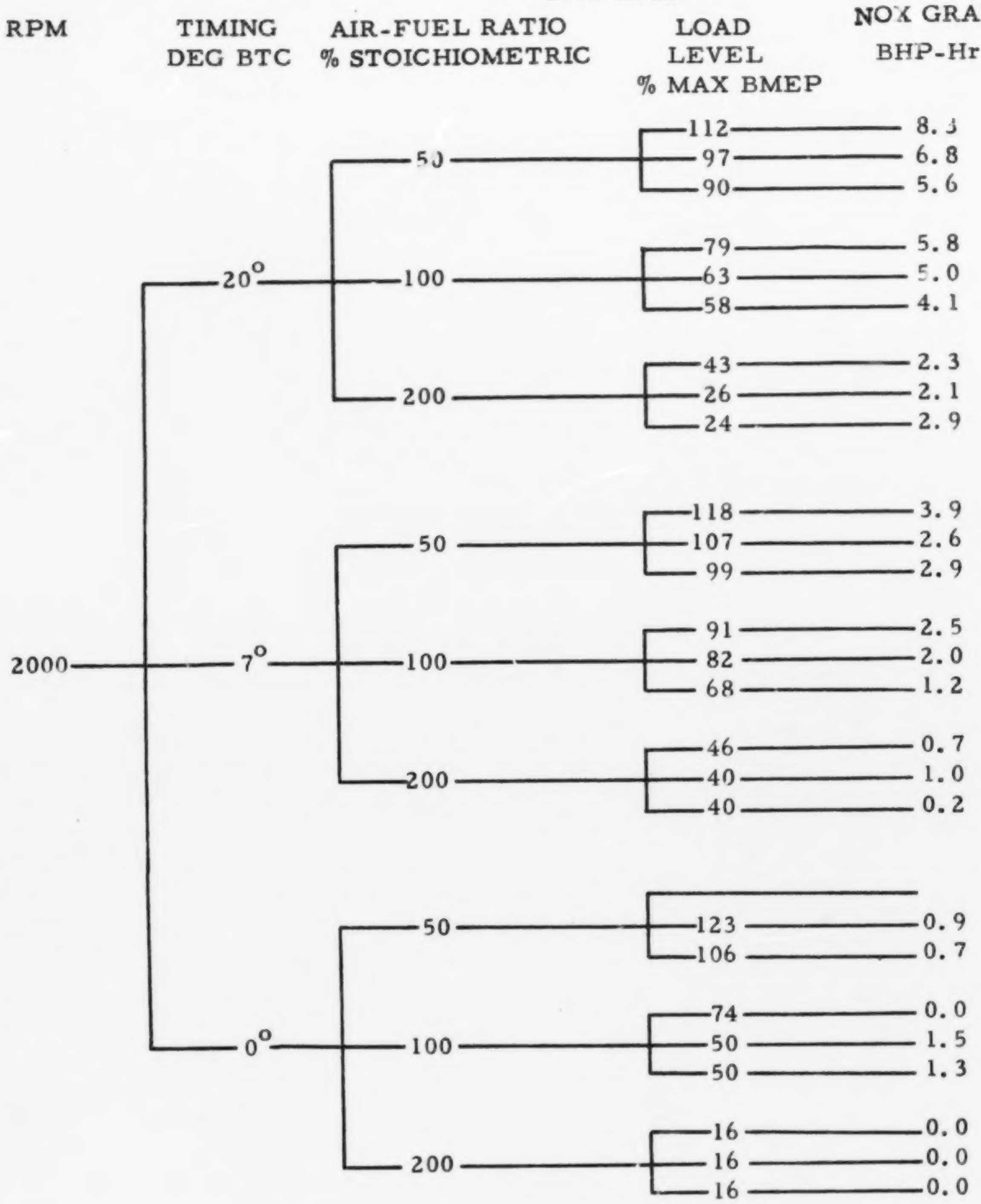

RPM
TIMING DEG BTC
AIR-FUEL RATIO % STOICHIOMETRIC
LOAD LEVEL % MAX BMEP
NOX GRAMS/ BHP-Hr
2000
20°
50
112
8.3
97
6.8
90
5.6
100
79
5.8
63
5.0
58
4.1
200
43
2.3
26
2.1
24
2.9
7°
50
118
3.9
107
2.6
99
2.9
100
91
2.5
82
2.0
68
1.2
200
46
0.7
40
1.0
40
0.2
0°
50
123
0.9
106
0.7
100
74
0.0
50
1.5
50
1.3
200
16
0.0
16
0.0
16
0.0

Figure 16B

TREE DIAGRAM--OXIDES OF NITROGEN EMISSION-- OAP FORMAT

-2500 RPM-

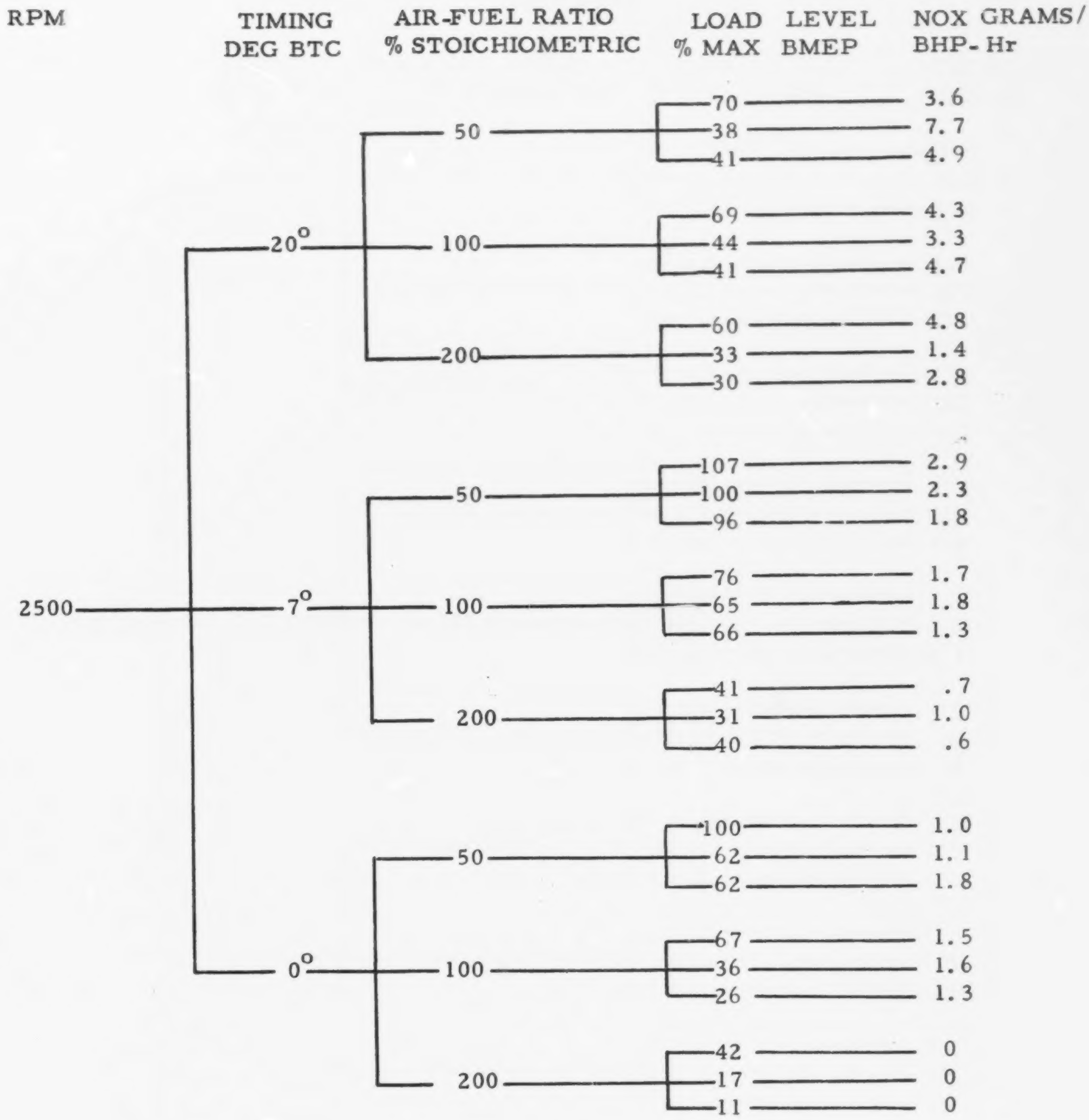

RPM
TIMING DEG BTC
AIR-FUEL RATIO % STOICHIOMETRIC
LOAD LEVEL % MAX BMEP
NOX GRAMS/ BHP-Hr
2500
20°
50
70 3.6
38 7.7
41 4.9
100
69 4.3
44 3.3
41 4.7
200
60 4.8
33 1.4
30 2.8
7°
50
107 2.9
100 2.3
96 1.8
100
76 1.7
65 1.8
66 1.3
200
41 .7
31 1.0
40 .6
0°
50
100 1.0
62 1.1
62 1.8
100
67 1.5
36 1.6
26 1.3
200
42 0
17 0
11 0

Figure 16C

TREE DIAGRAM--OXIDES OF NITROGEN EMISSION-- OAP FORMAT
-3000 RPM-

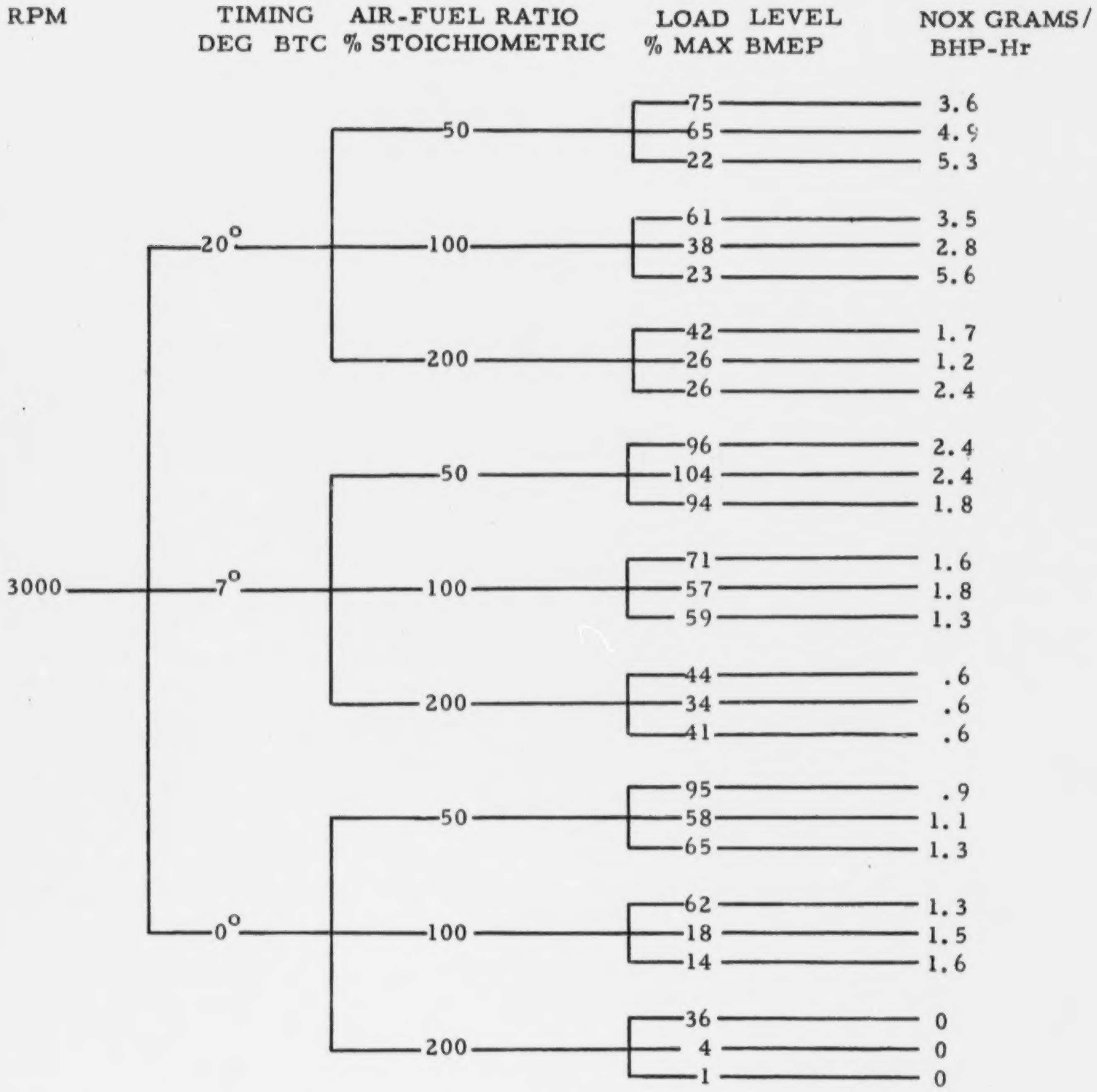

RPM
TIMING DEG BTC
AIR-FUEL RATIO % STOICHIOMETRIC
LOAD LEVEL % MAX BMEP
NOX GRAMS/ BHP-Hr
3000
20°
50
75 — 3.6
65 — 4.9
22 — 5.3
100
61 — 3.5
38 — 2.8
23 — 5.6
200
42 — 1.7
26 — 1.2
26 — 2.4
7°
50
96 — 2.4
104 — 2.4
94 — 1.8
100
71 — 1.6
57 — 1.8
59 — 1.3
200
44 — .6
34 — .6
41 — .6
0°
50
95 — .9
58 — 1.1
65 — 1.3
100
62 — 1.3
18 — 1.5
14 — 1.6
200
36 — 0
4 — 0
1 — 0

Figure 16D

TREE DIAGRAM--OXIDES OF NITROGEN-- OAP FORMAT
-3500 RPM-

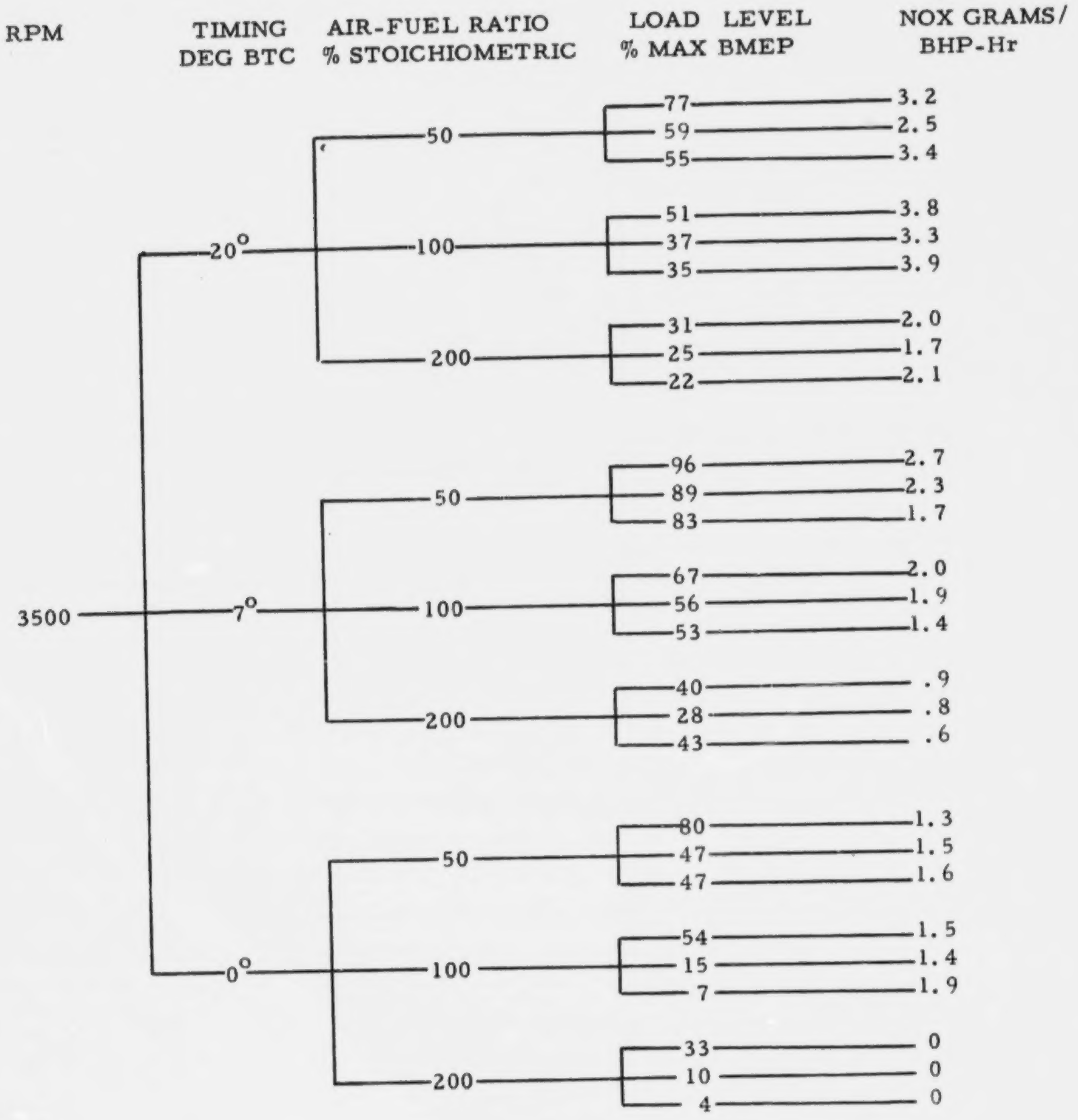
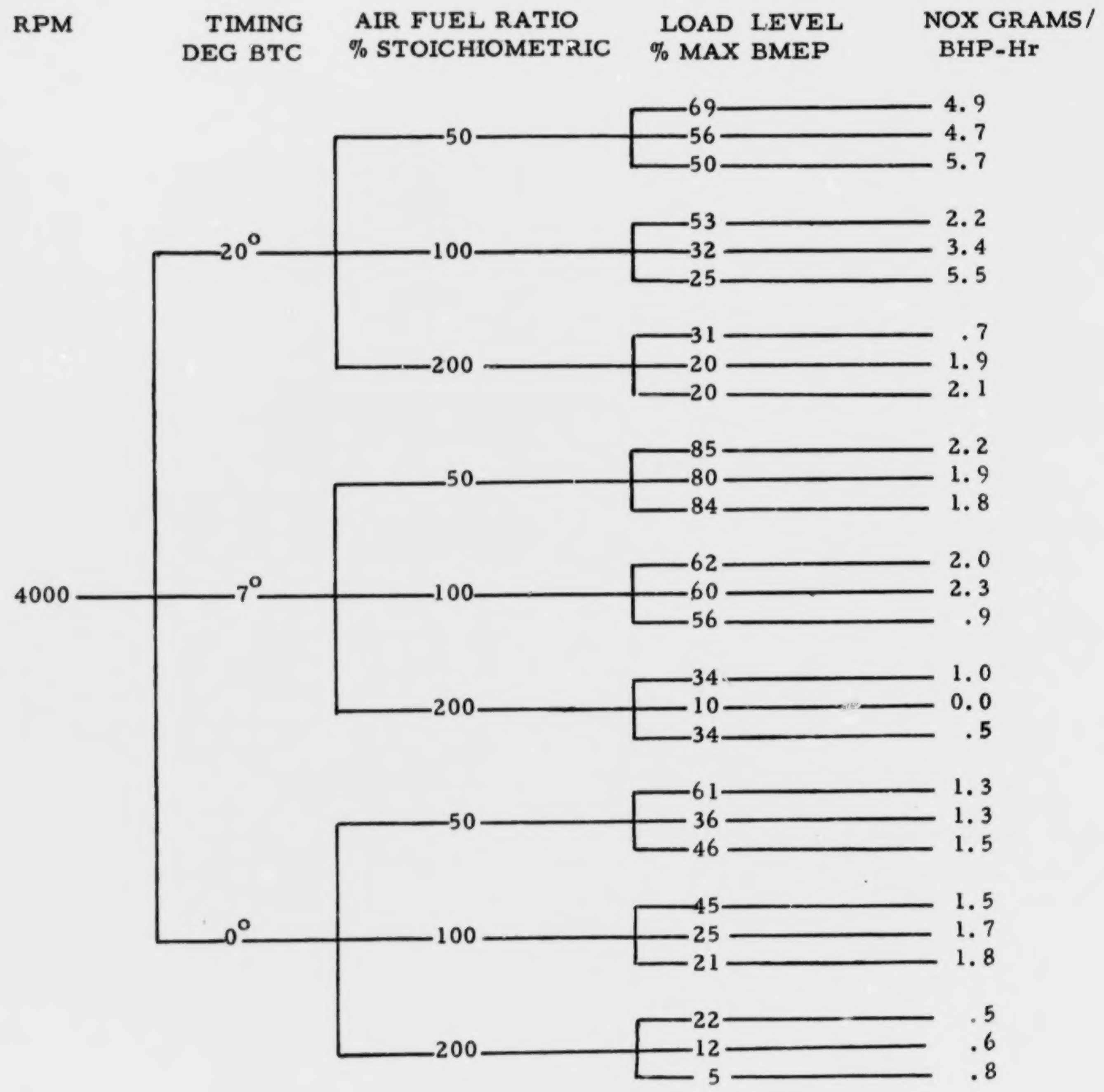

RPM
TIMING DEG BTC
AIR-FUEL RATIO % STOICHIOMETRIC
LOAD LEVEL % MAX BMEP
NOX GRAMS/ BHP-Hr
3500
20°
50
77
3.2
59
2.5
55
3.4
100
51
3.8
37
3.3
35
3.9
200
31
2.0
25
1.7
22
2.1
7°
50
96
2.7
89
2.3
83
1.7
100
67
2.0
56
1.9
53
1.4
200
40
.9
28
.8
43
.6
0°
50
80
1.3
47
1.5
47
1.6
100
54
1.5
15
1.4
7
1.9
200
33
0
10
0
4
0

Figure 16E

TREE DIAGRAM--OXIDES OF NITROGEN EMISSION-- OAP FORMAT
-4000 RPM-


RPM
TIMING DEG BTC
AIR FUEL RATIO % STOICHIOMETRIC
LOAD LEVEL % MAX BMEP
NOX GRAMS/ BHP-Hr
4000
20°
50
69 4.9
56 4.7
50 5.7
100
53 2.2
32 3.4
25 5.5
200
31 .7
20 1.9
20 2.1
7°
50
85 2.2
80 1.9
84 1.8
100
62 2.0
60 2.3
56 .9
200
34 1.0
10 0.0
34 .5
0°
50
61 1.3
36 1.3
46 1.5
100
45 1.5
25 1.7
21 1.8
200
22 .5
12 .6
5 .8

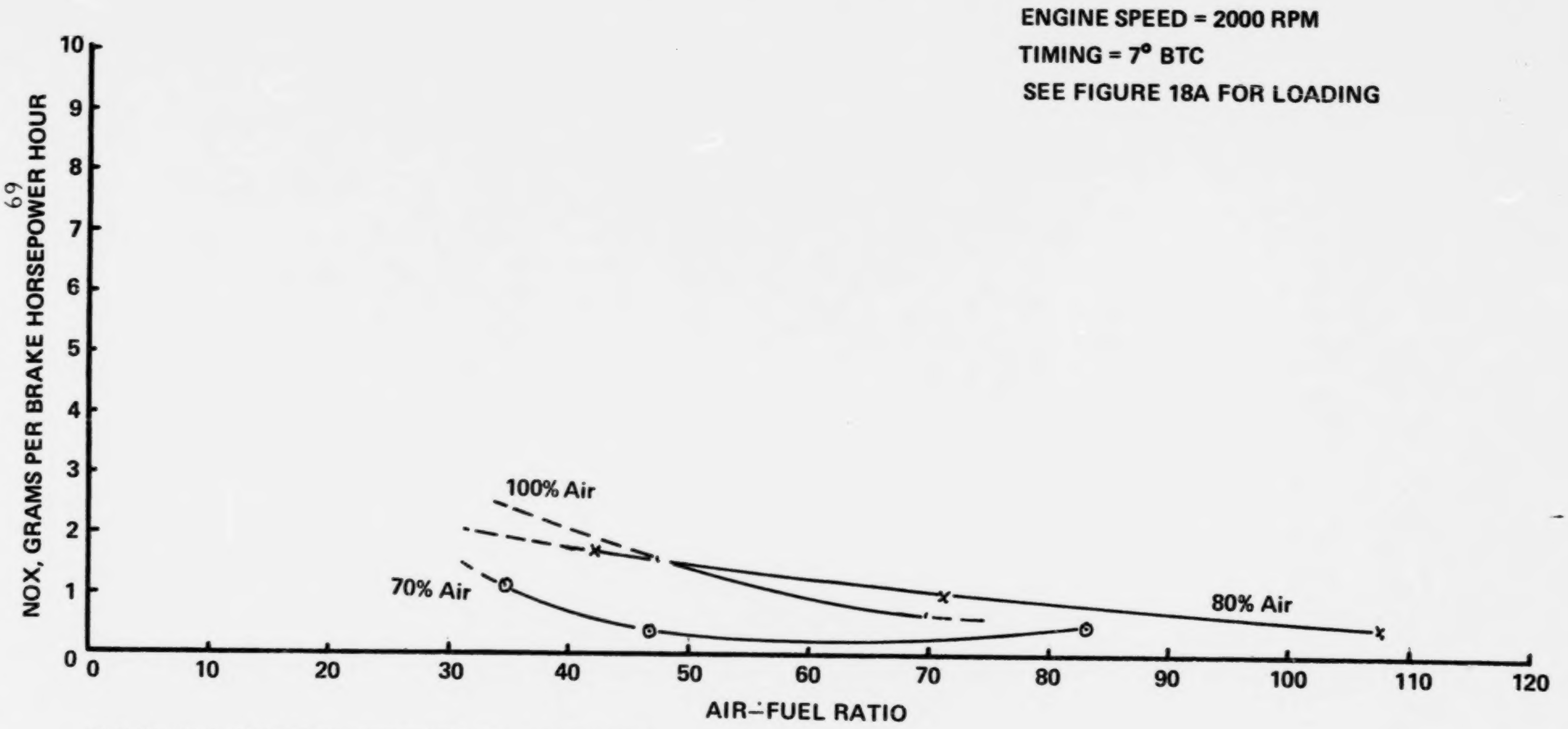


FIGURE 17A EMISSION–MIXTURE RELATIONSHIPS

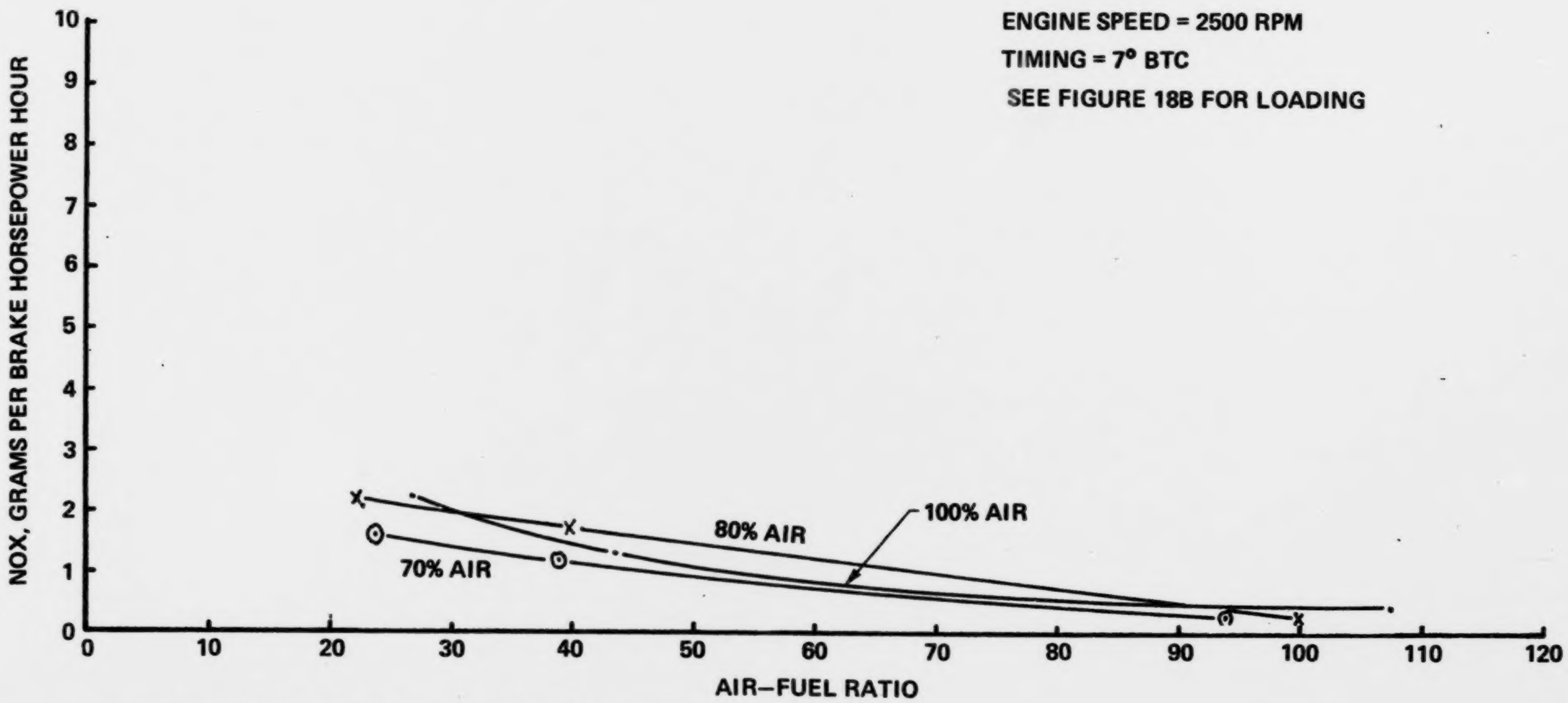


FIGURE 17B EMISSION–MIXTURE RELATIONSHIPS

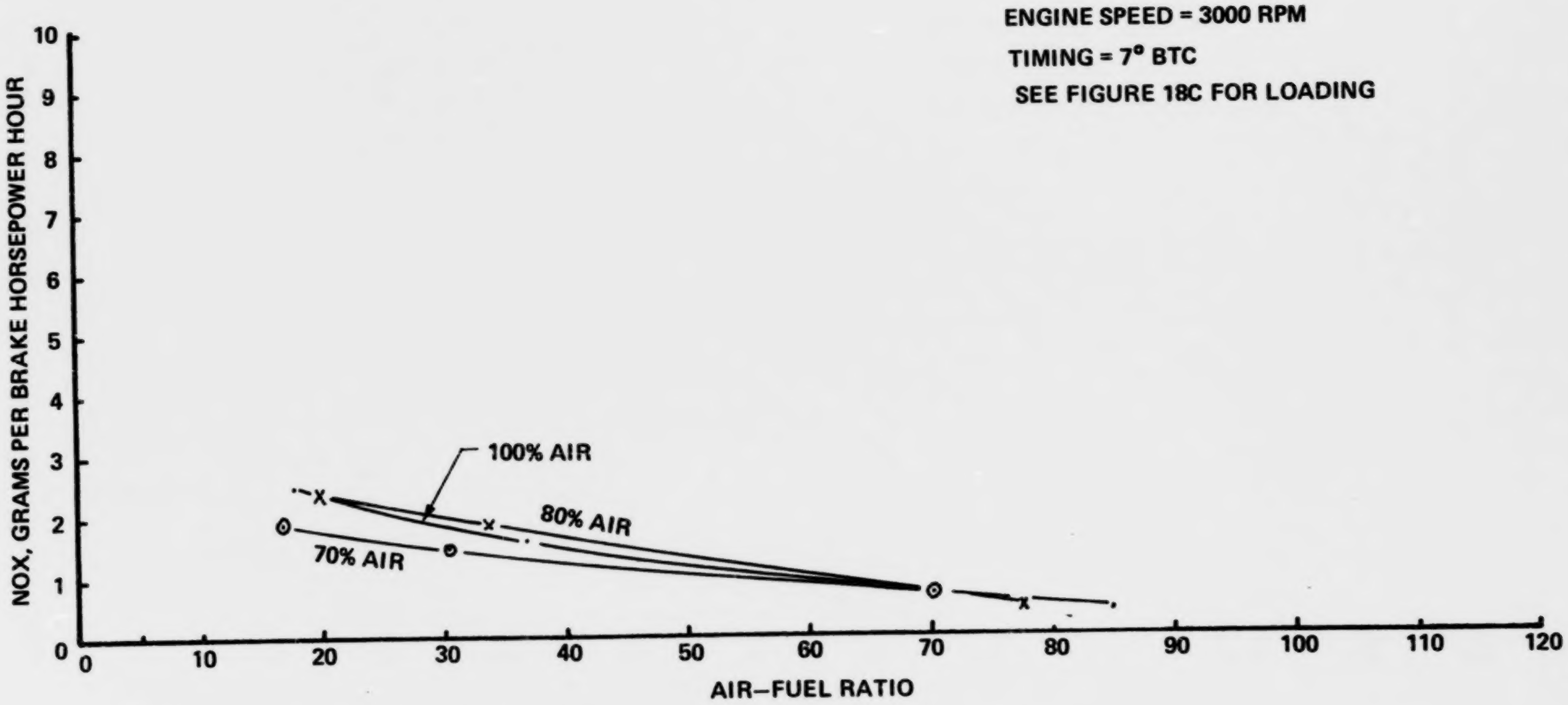
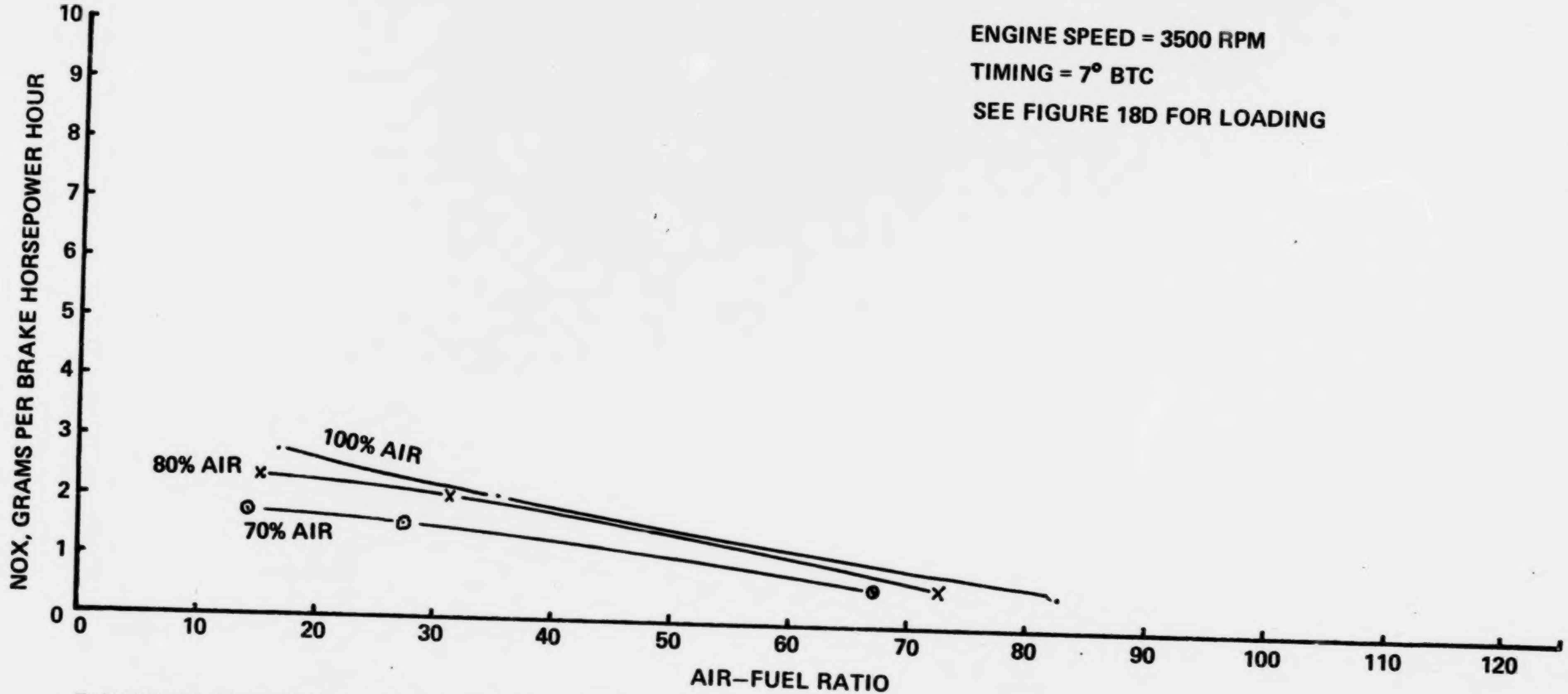
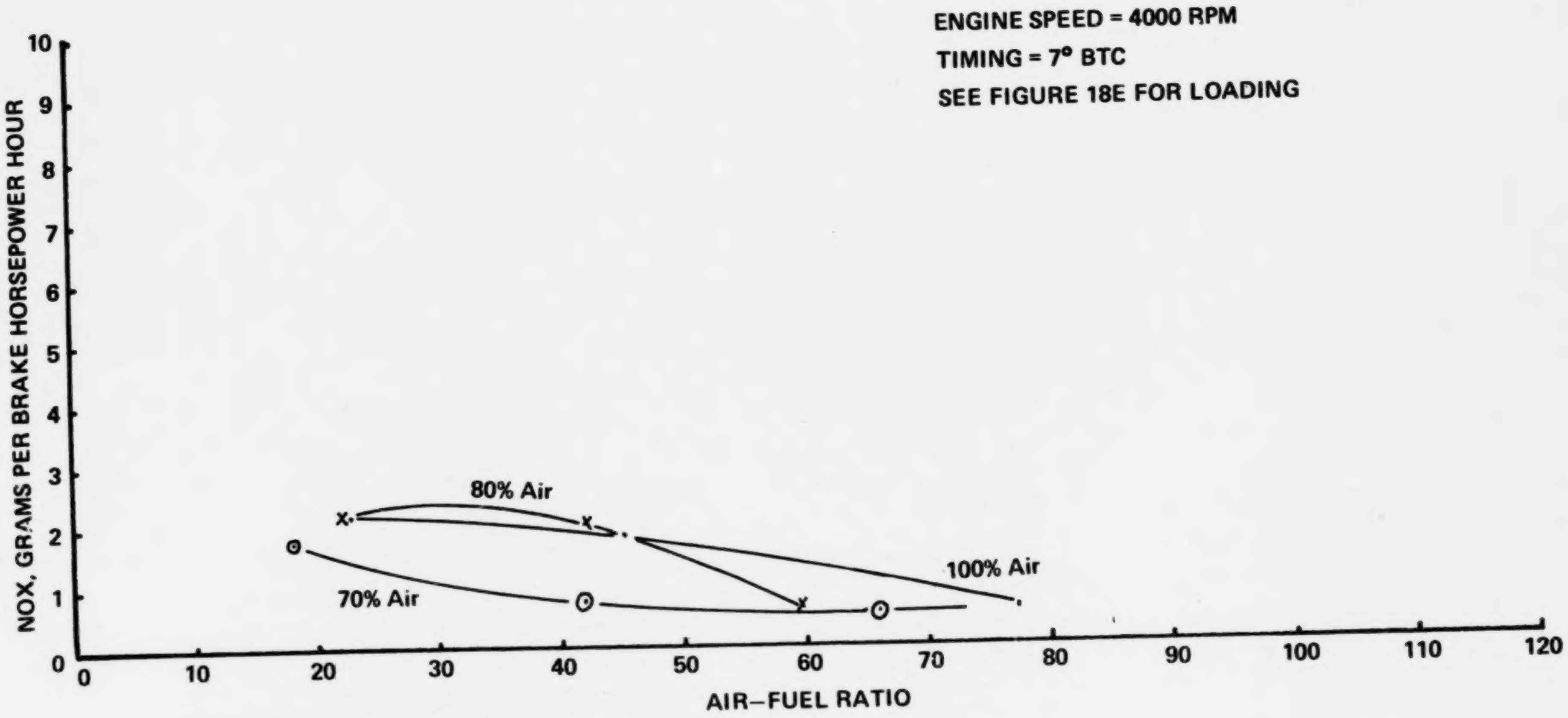


FIGURE 17C EMISSION–MIXTURE RELATIONSHIPS



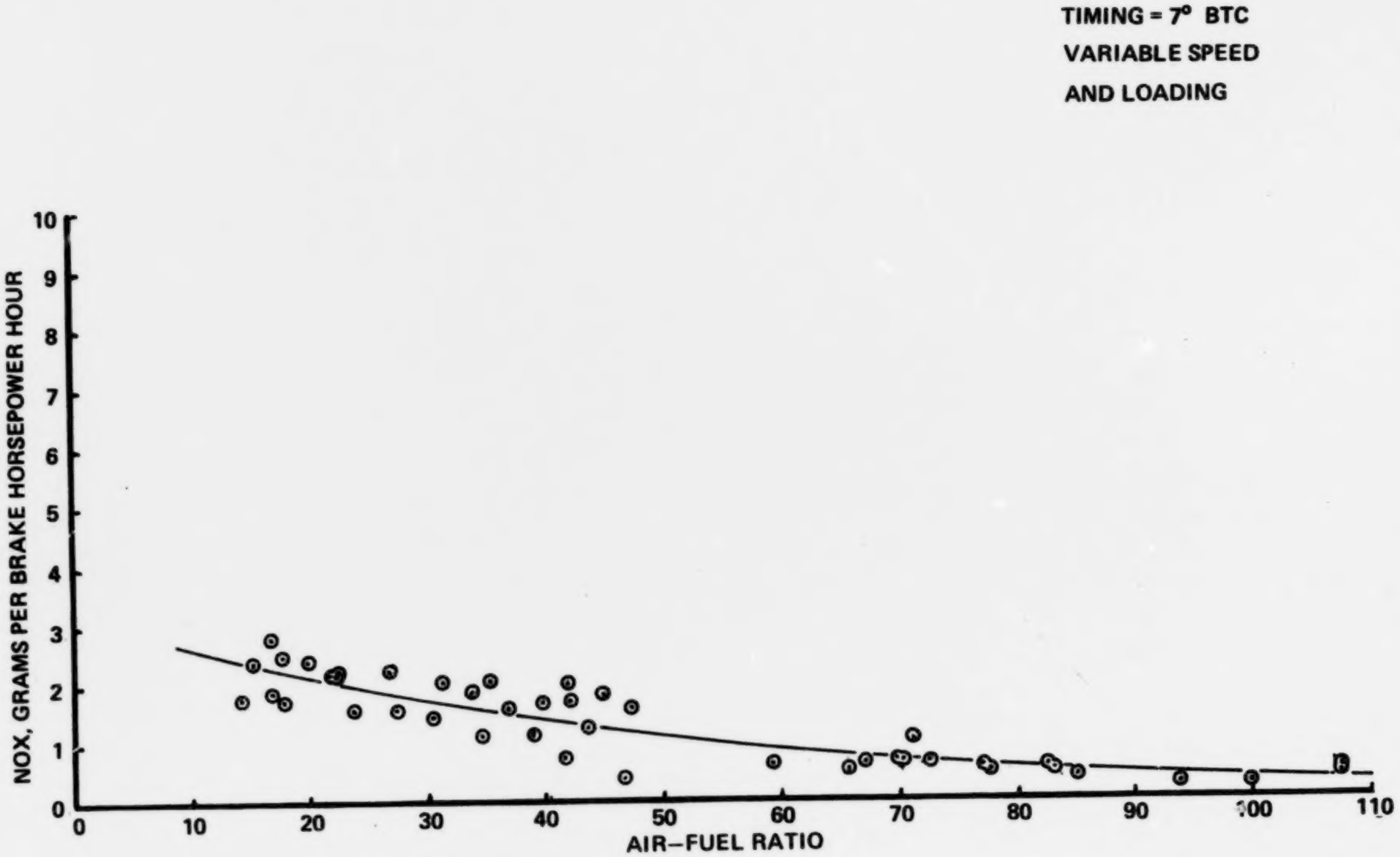
ENGINE SPEED = 3500 RPM
TIMING = 7° BTC
SEE FIGURE 18D FOR LOADING

FIGURE 17D EMISSION–MIXTURE RELATIONSHIPS



ENGINE SPEED = 4000 RPM
TIMING = 7° BTC
SEE FIGURE 18E FOR LOADING

FIGURE 17E EMISSION–MIXTURE RELATIONSHIPS



TIMING = 7° BTC
VARIABLE SPEED
AND LOADING

FIGURE 17F COMPOSITE PLOT OF FIGURES 17A–17E

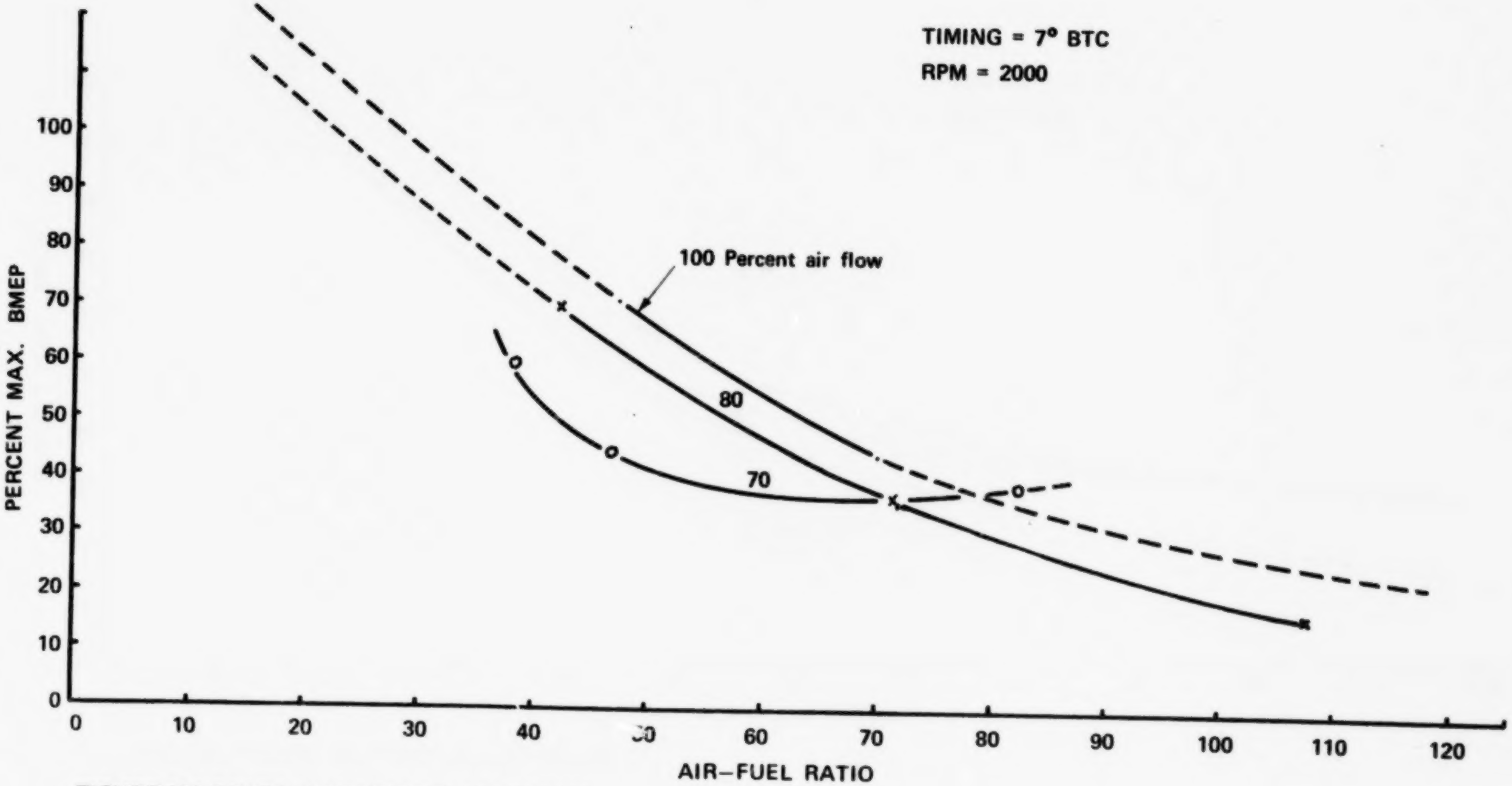


FIGURE 18A POWER–MIXTURE RELATIONSHIPS

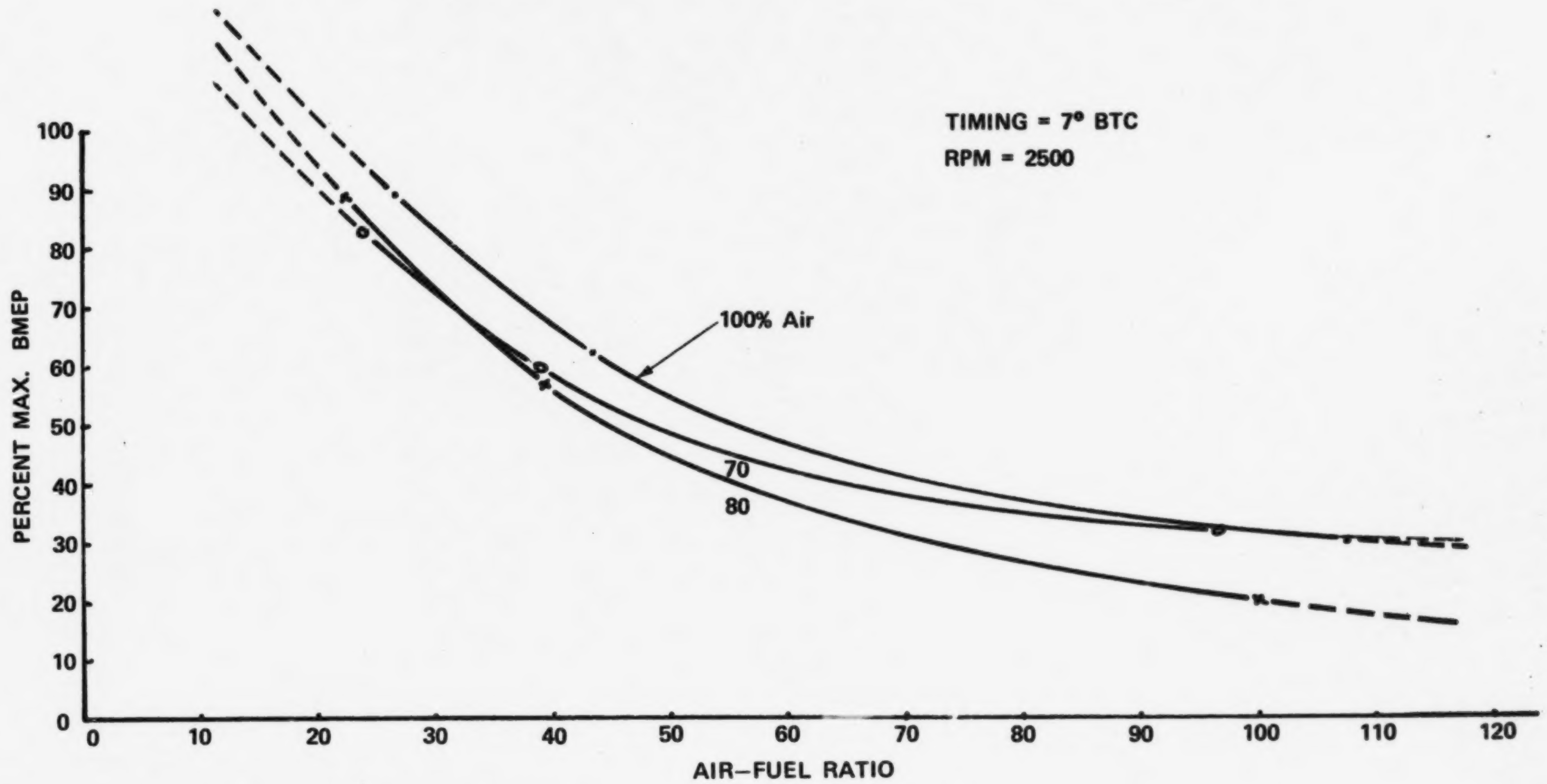


FIGURE 18B POWER–MIXTURE RELATIONSHIPS

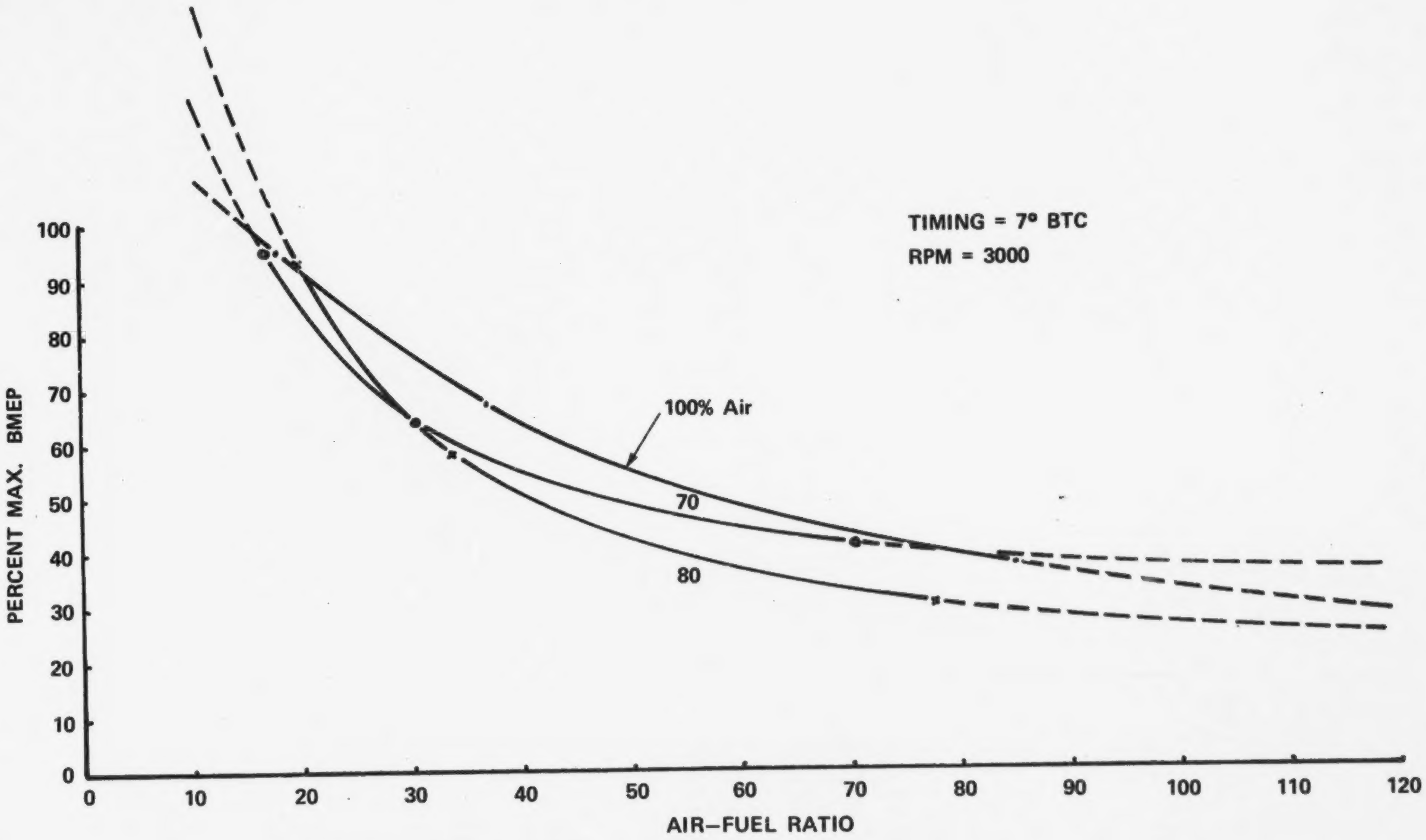


FIGURE 18C POWER–MIXTURE RELATIONSHIPS

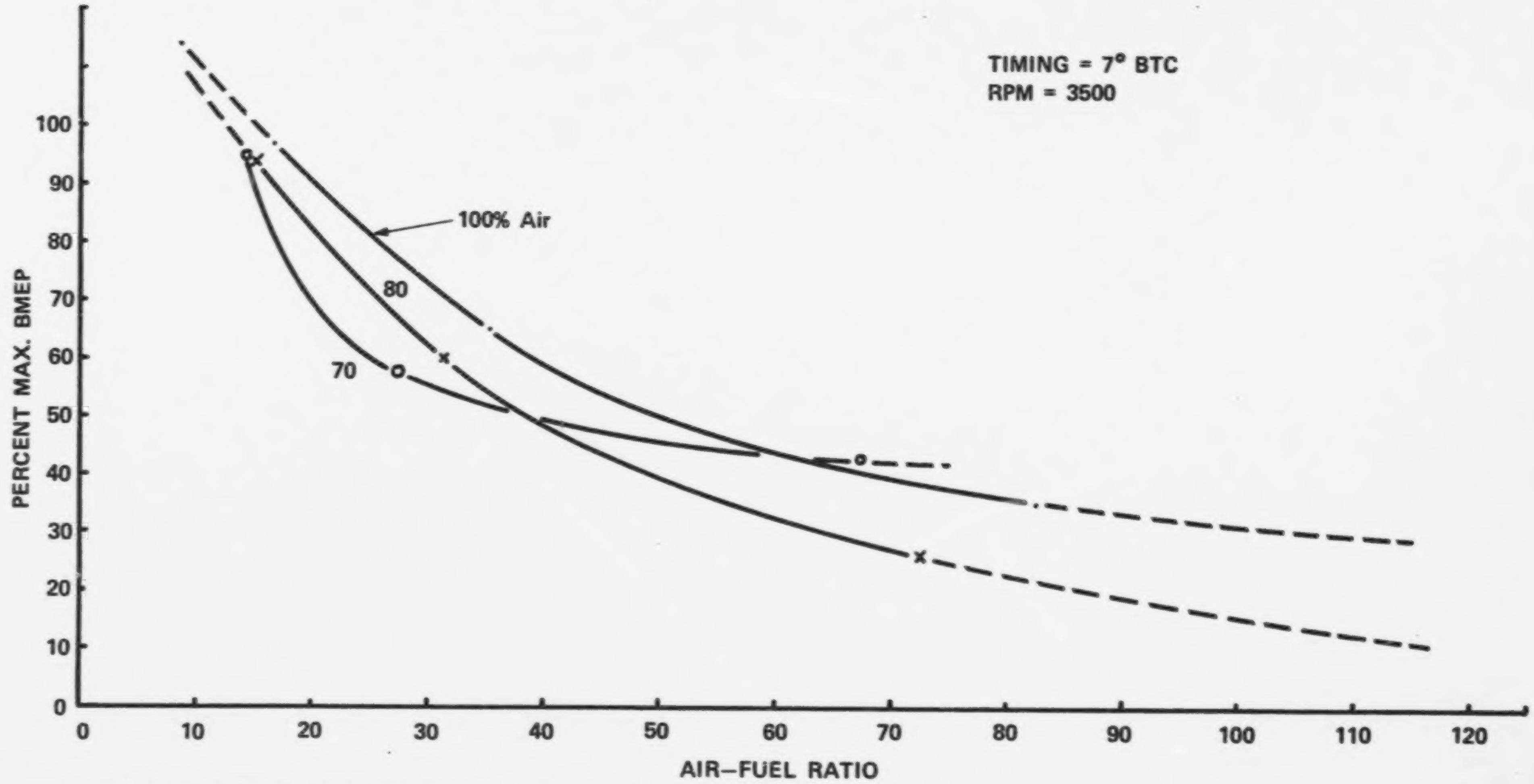


FIGURE 18D POWER–MIXTURE RELATIONSHIPS

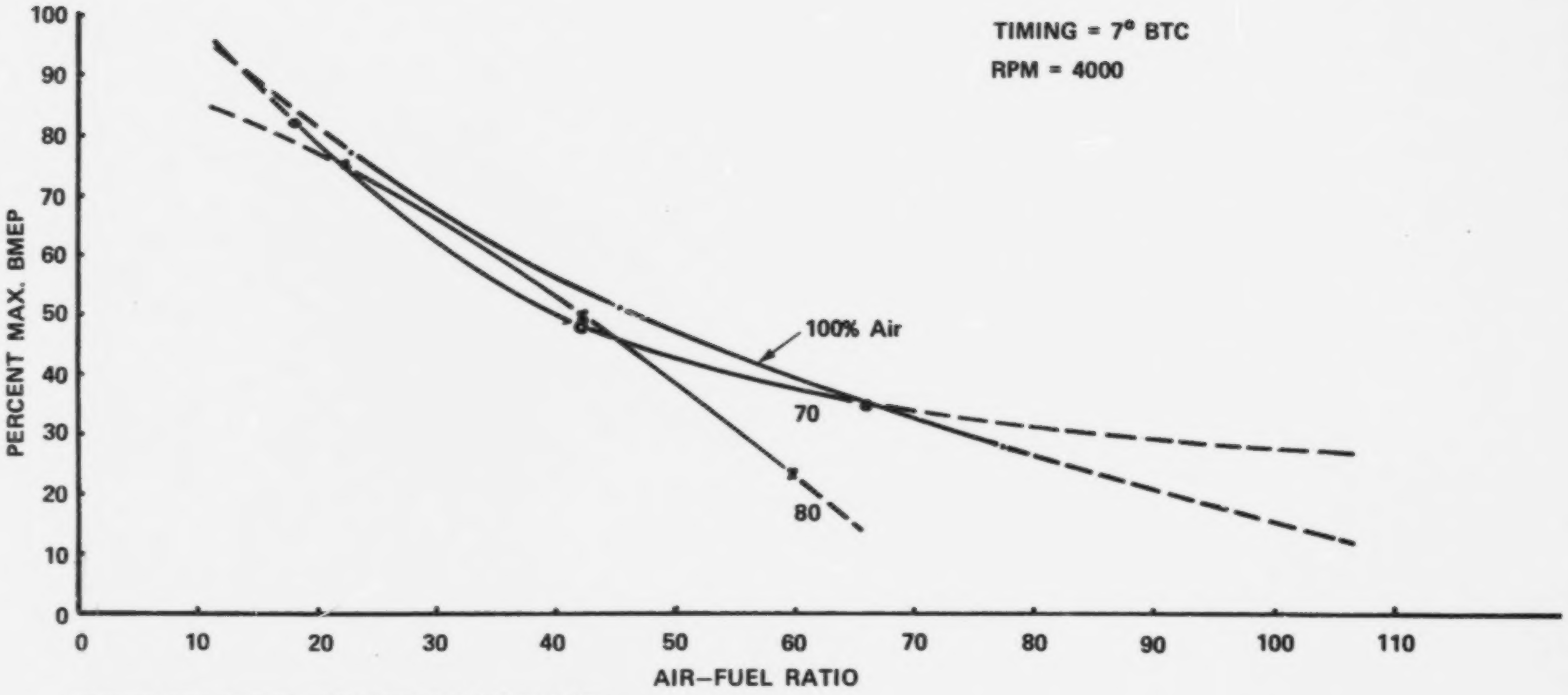


FIGURE 18E POWER–MIXTURE RELATIONSHIPS

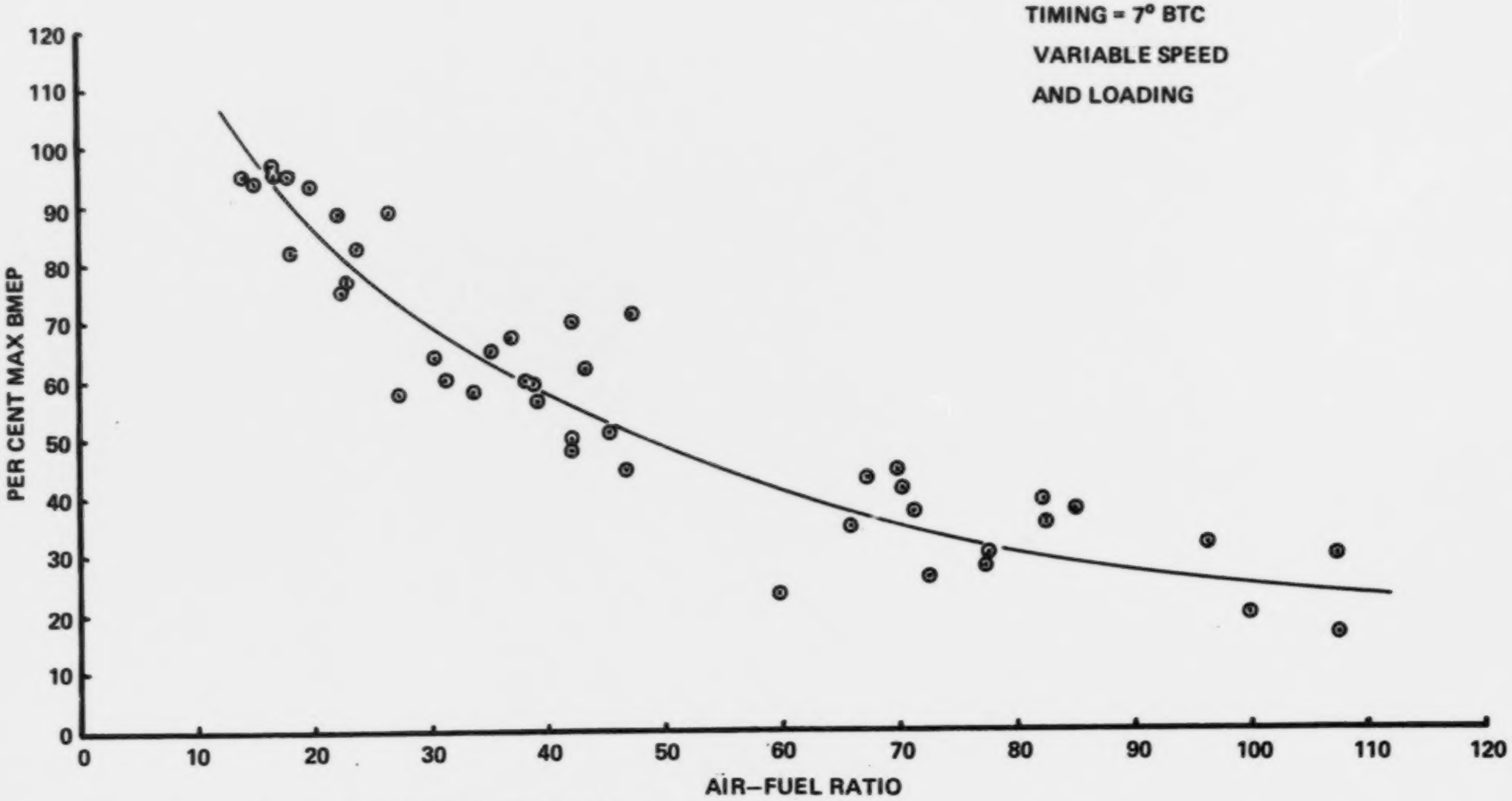


FIGURE 18F – COMPOSITE PLOT OF FIGURES 18A–18E

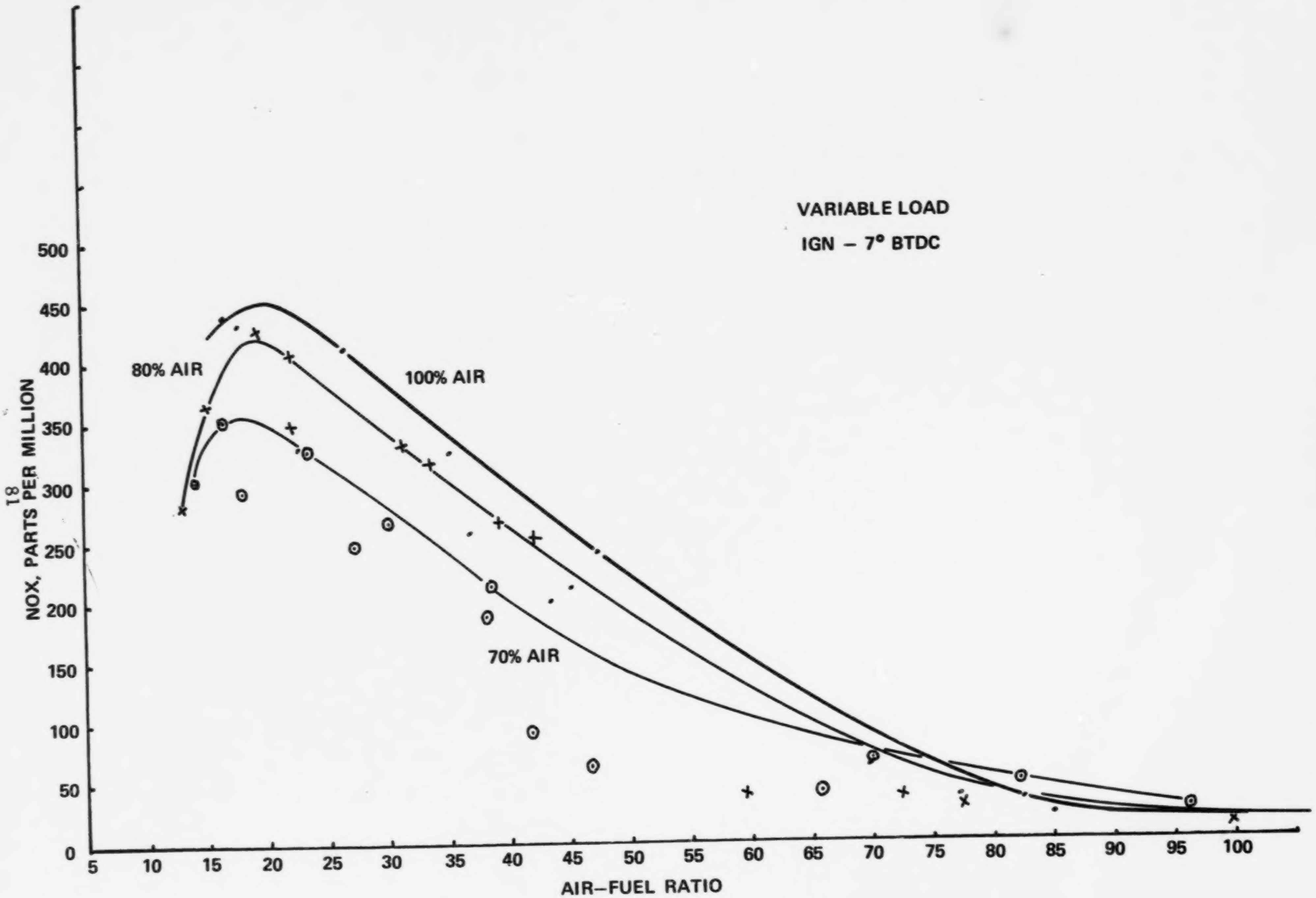


FIGURE I9 EMISSION CONCENTRATION

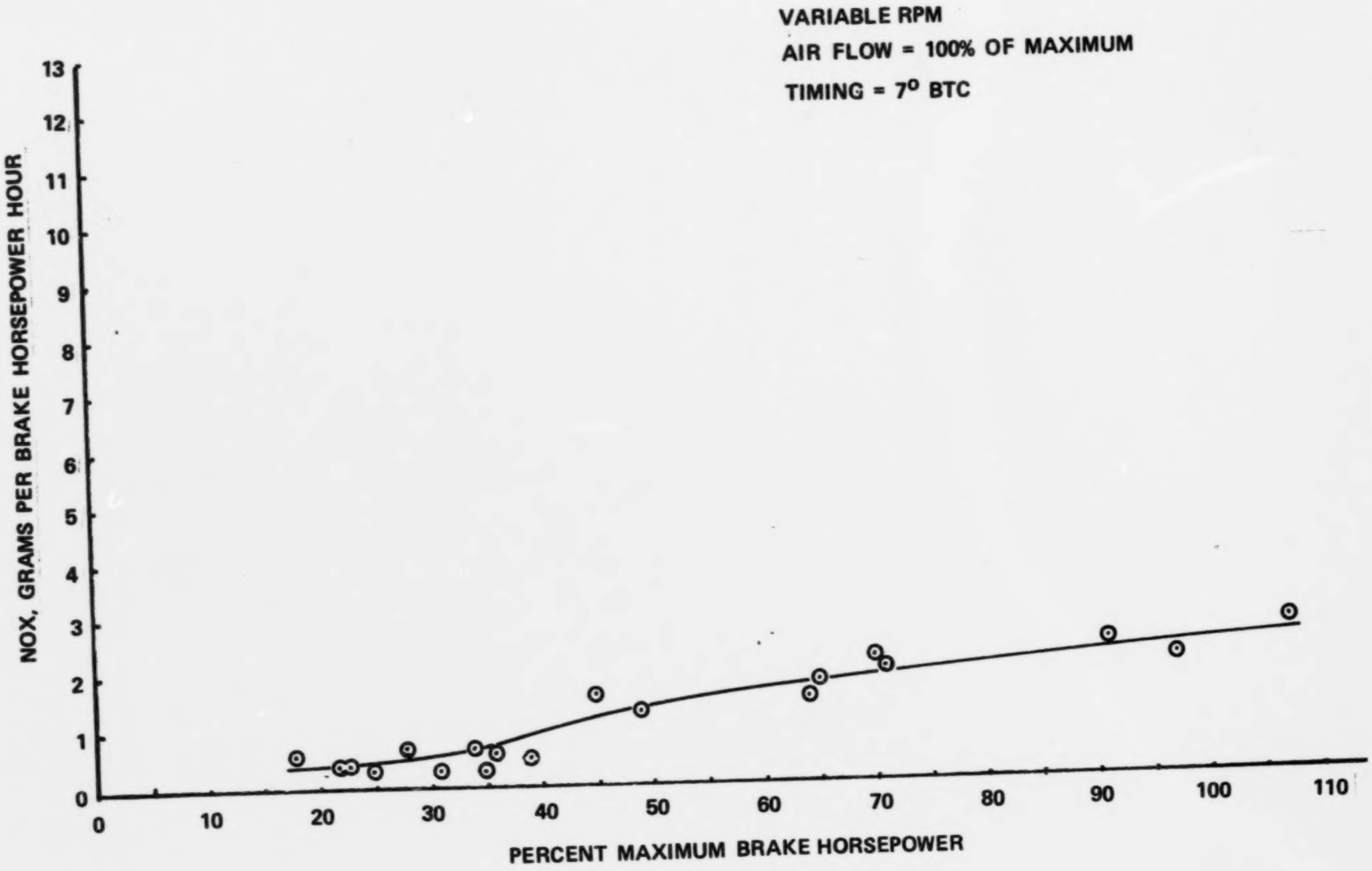


FIGURE 20A EMISSION–POWER RELATIONSHIPS

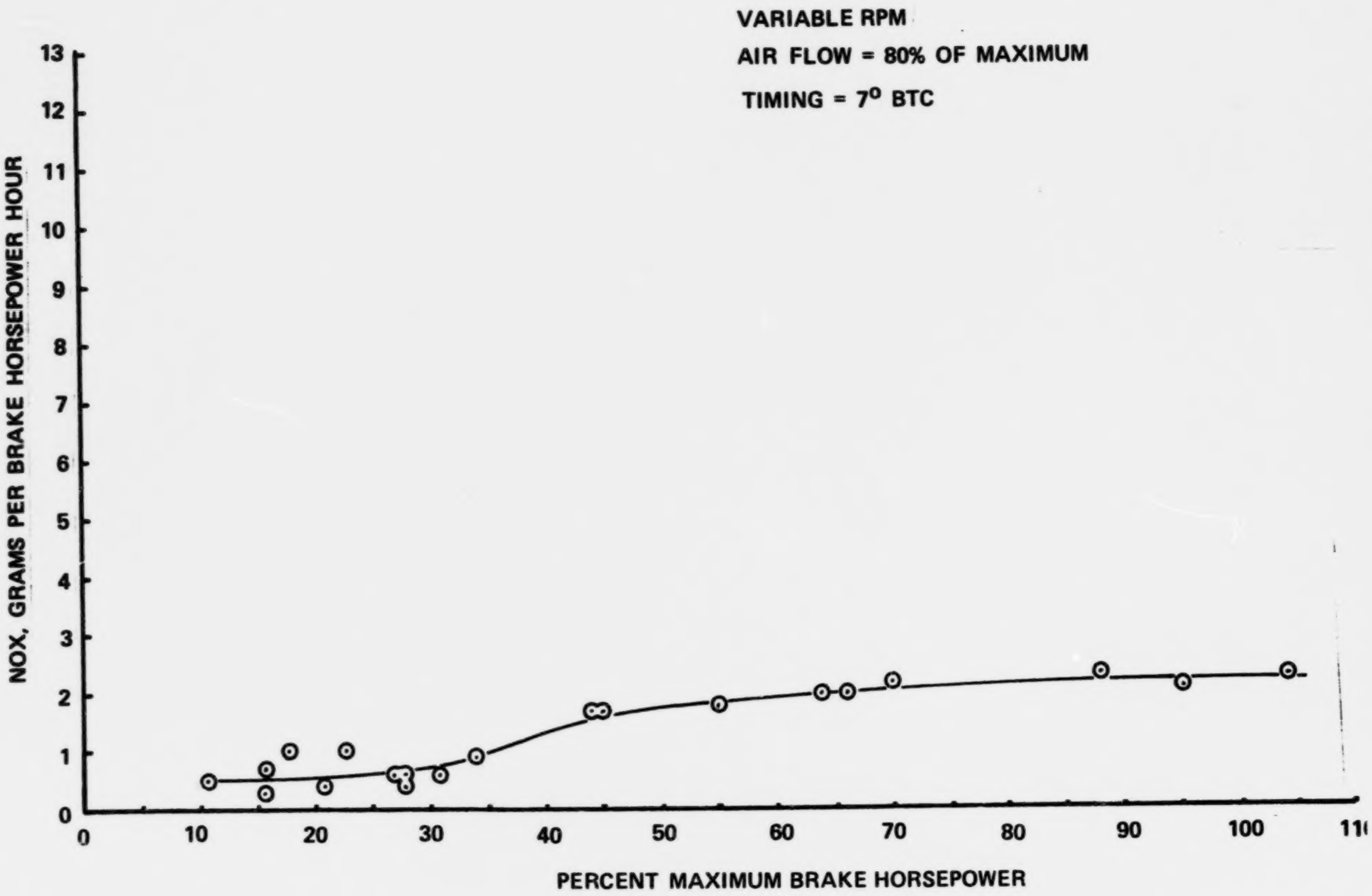


FIGURE 20B EMISSION–POWER RELATIONSHIPS

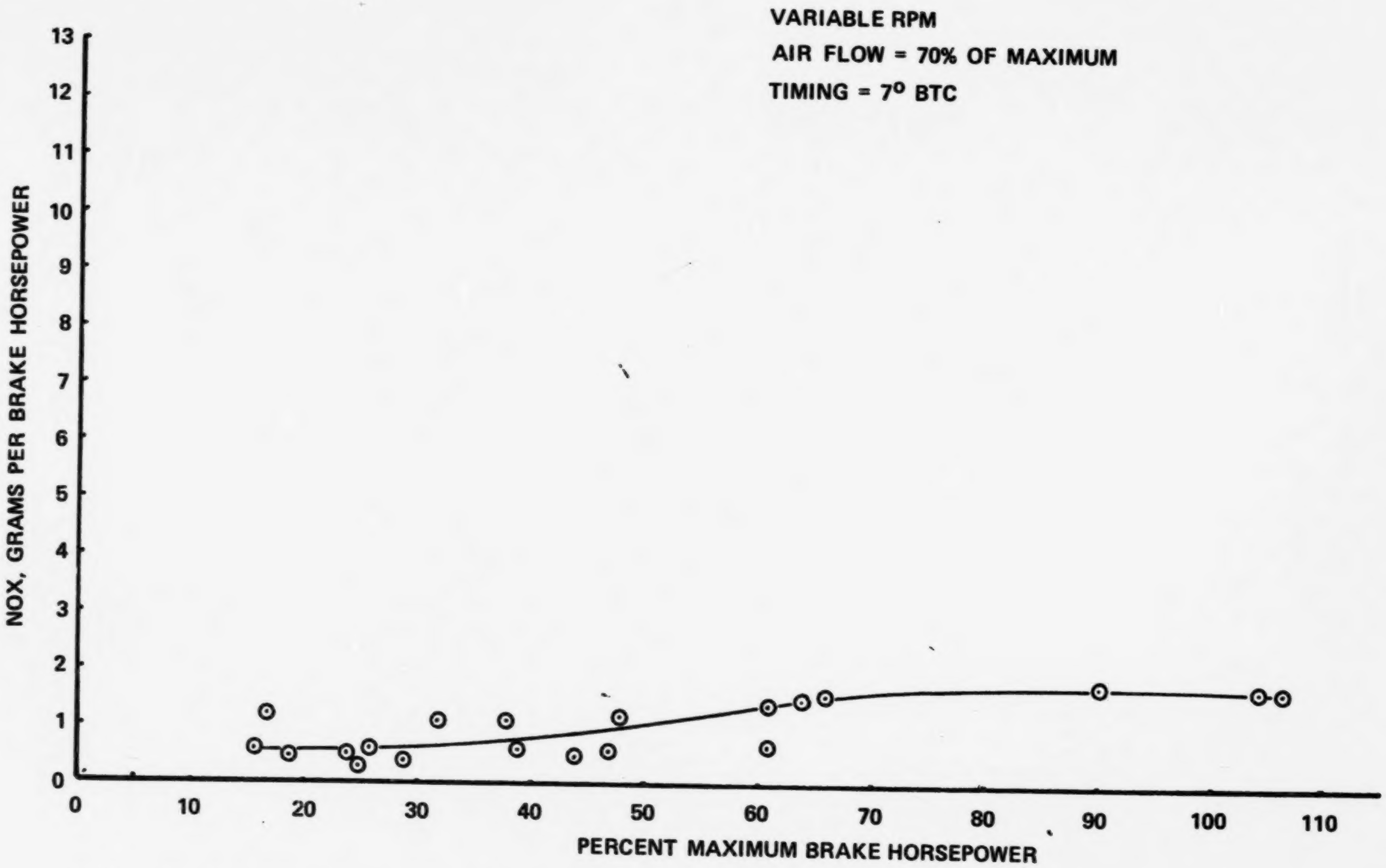


FIGURE 20C EMISSION—POWER RELATIONSHIPS

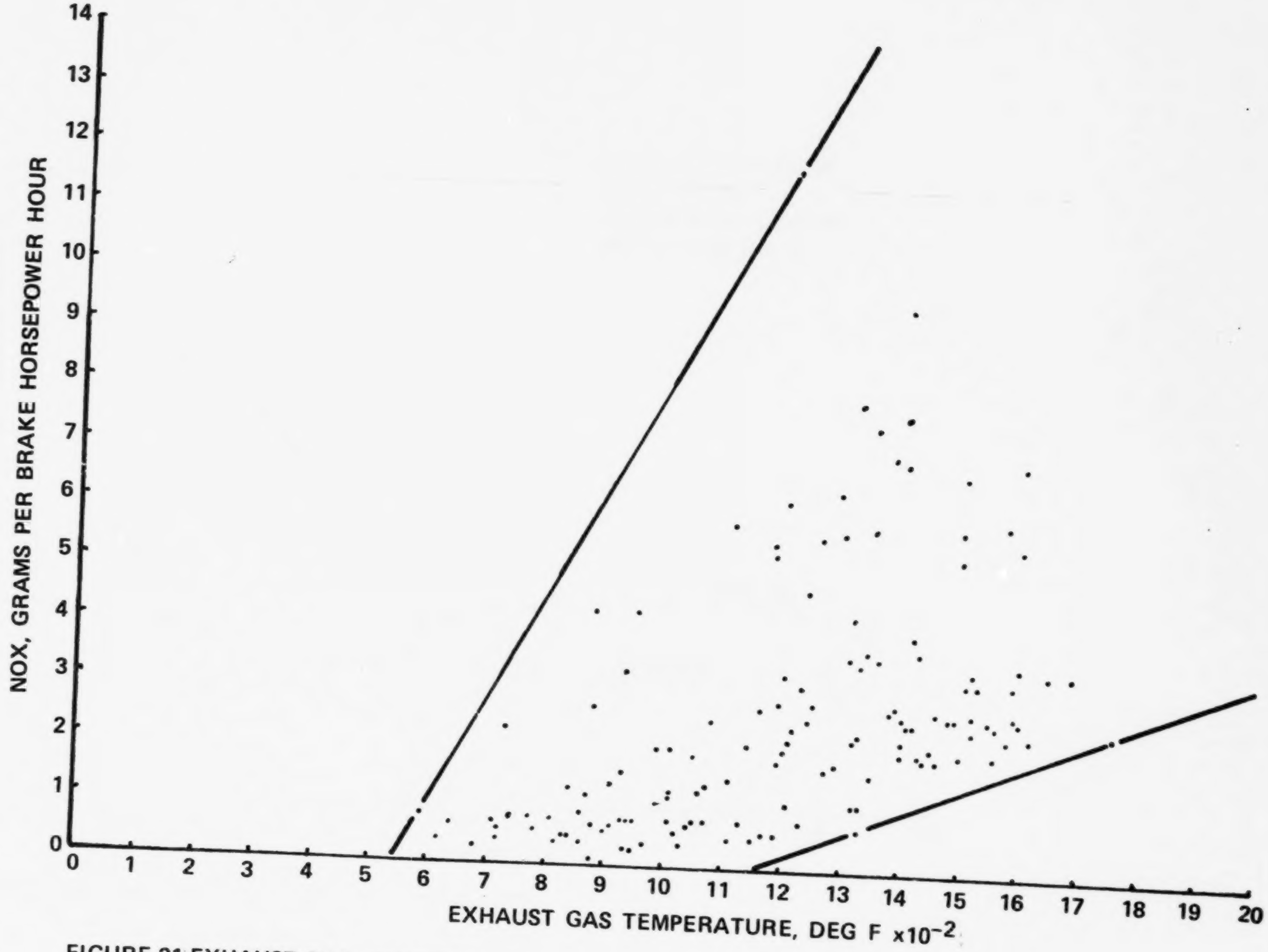


FIGURE 21 EXHAUST GAS TEMPERATURE

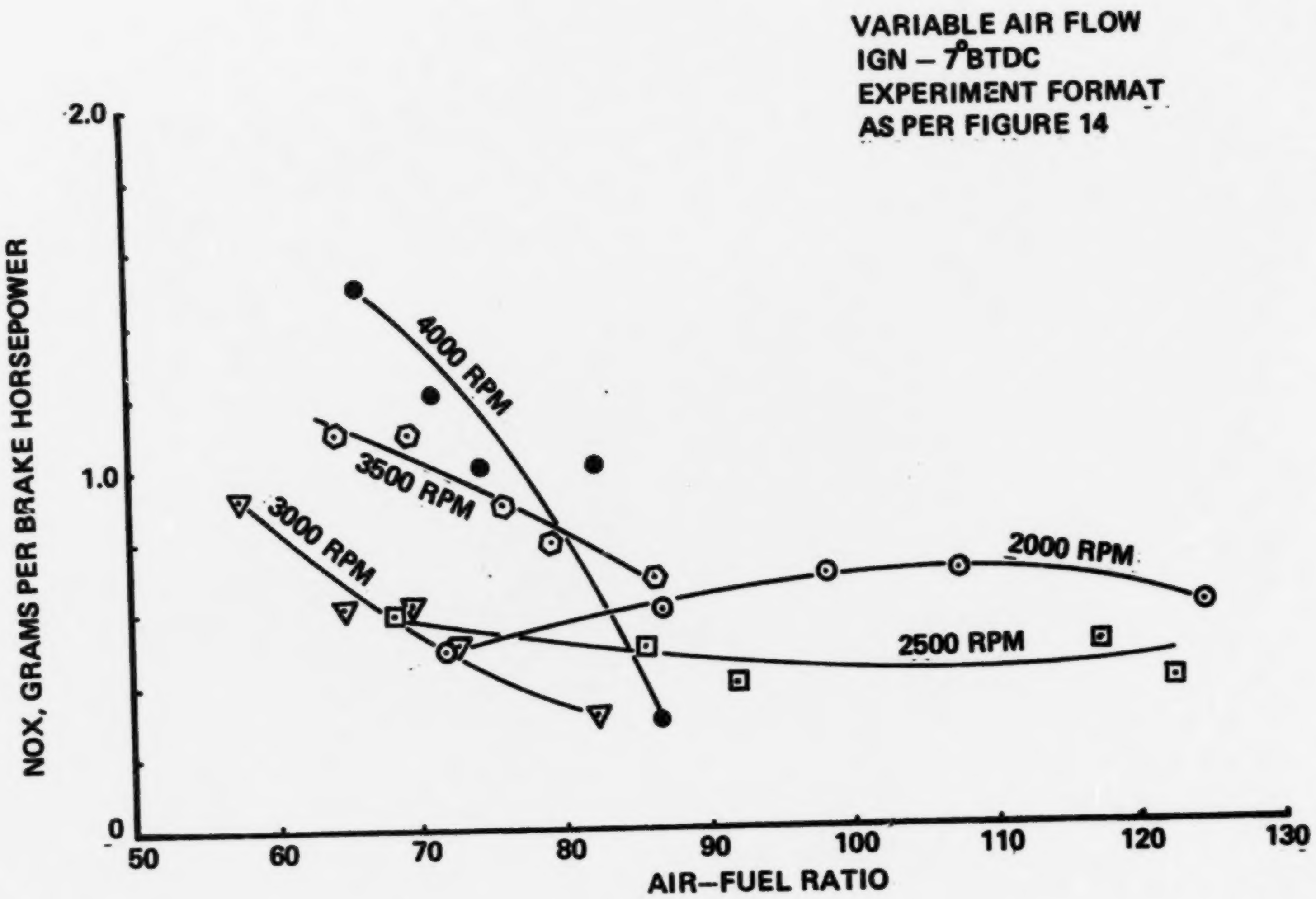


FIGURE 22A EMISSION–MIXTURE RELATIONSHIPS

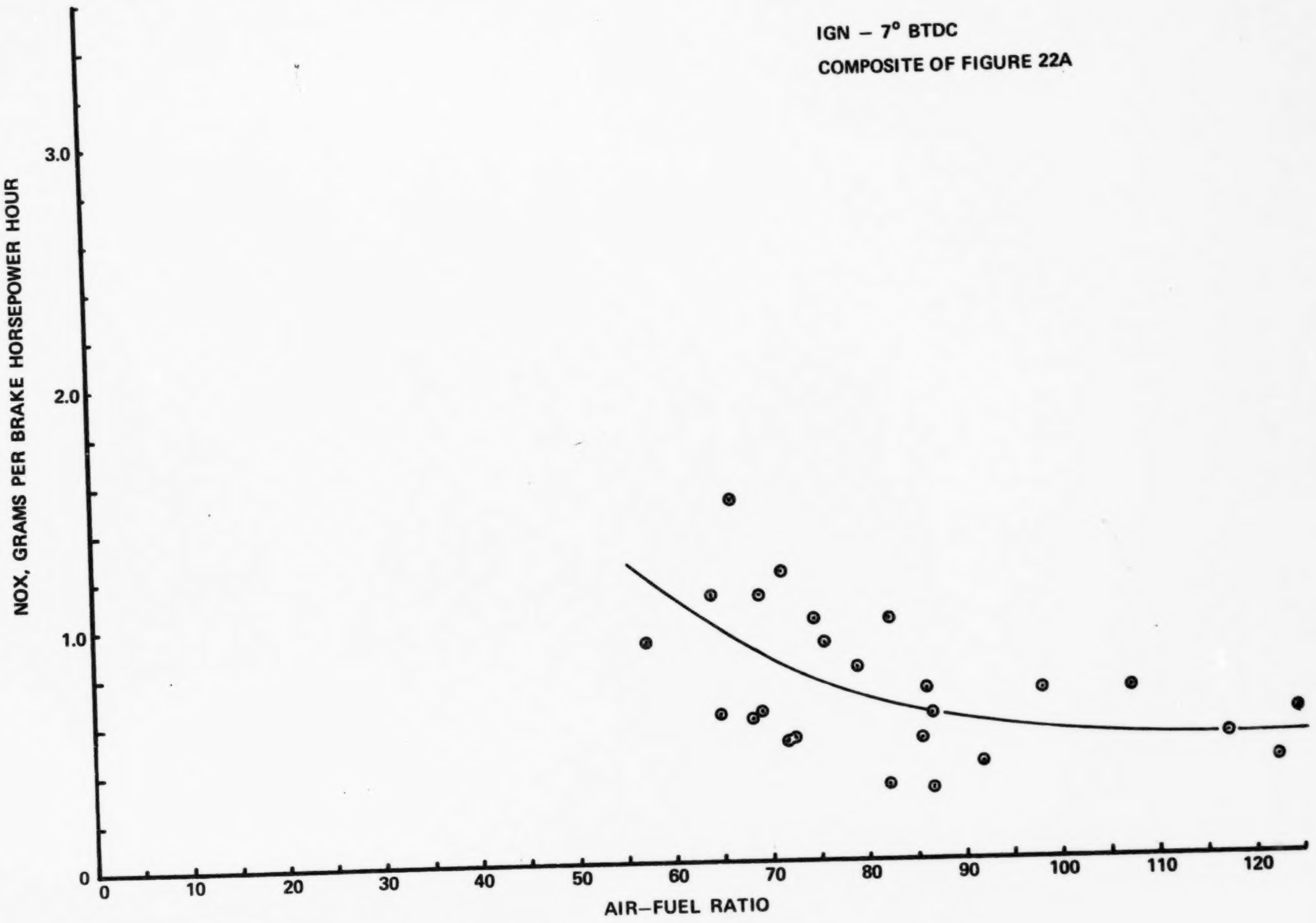
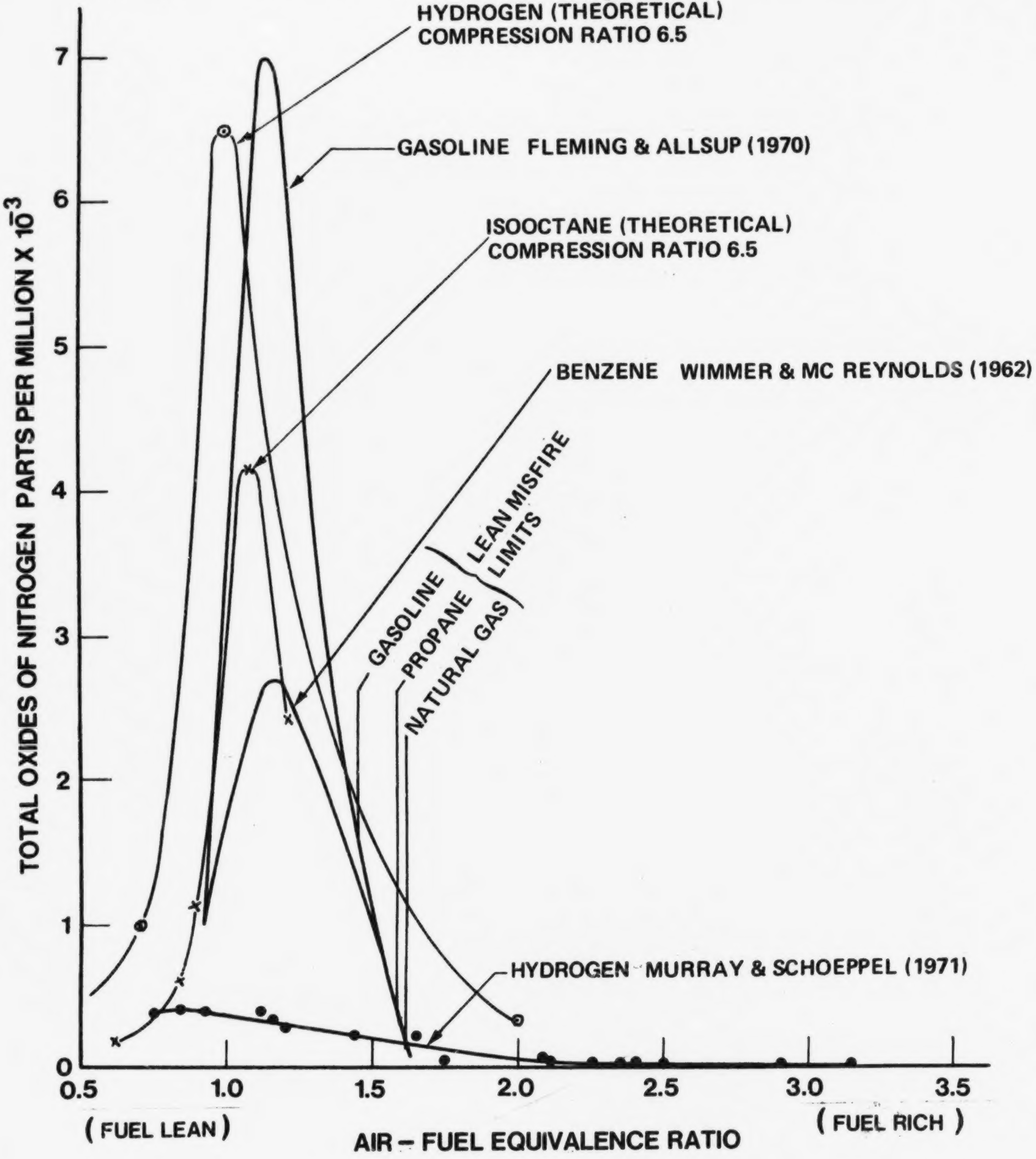


FIGURE 22B EMISSION-MIXTURE RELATIONSHIPS

FIGURE 23 WIDE-OPEN THROTTLE EMISSION CHARACTERISTICS



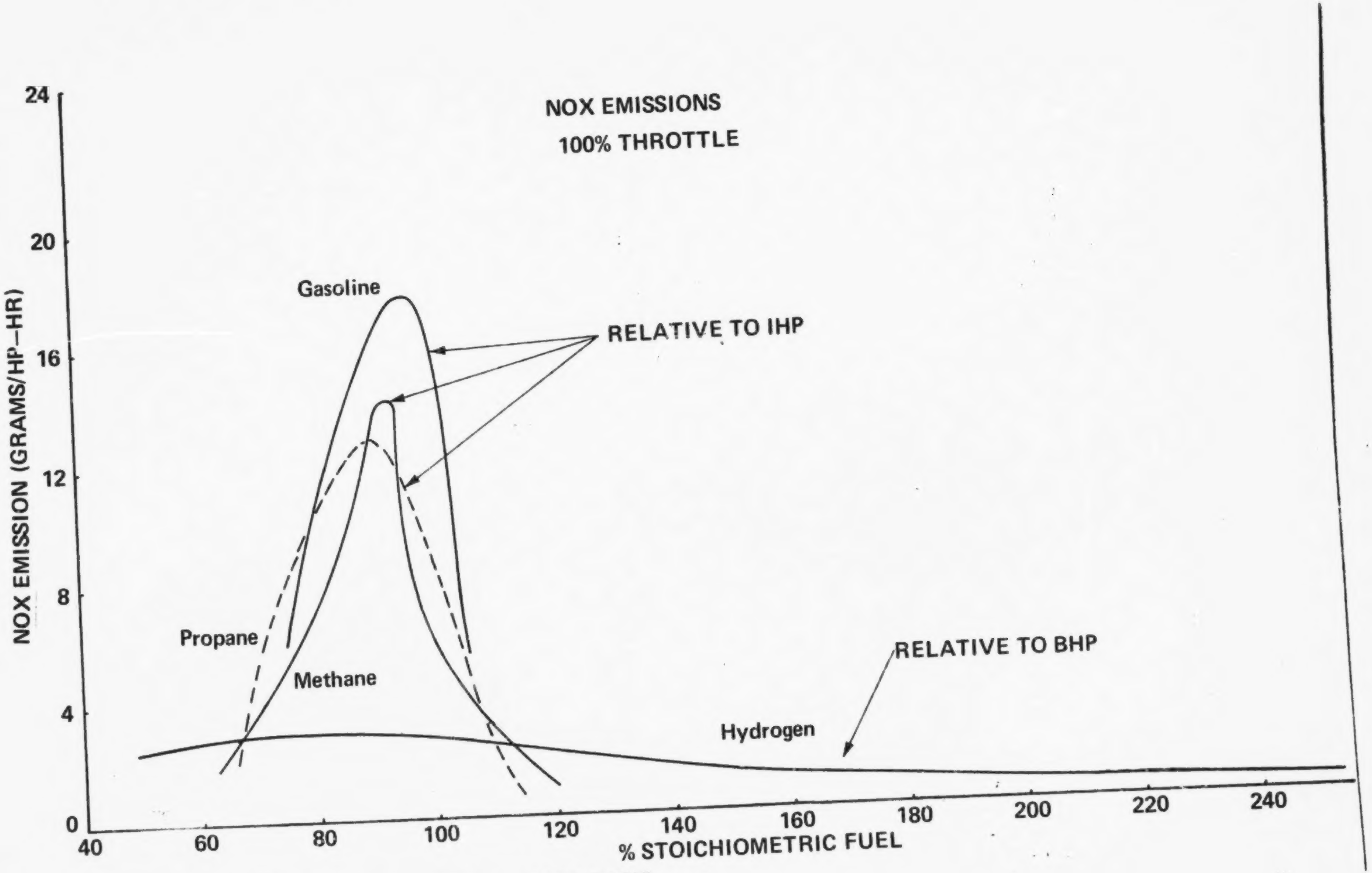


FIGURE 24 COMPARATIVE EMISSIONS–MASS BASIS

NOT REPRODUCIBLE

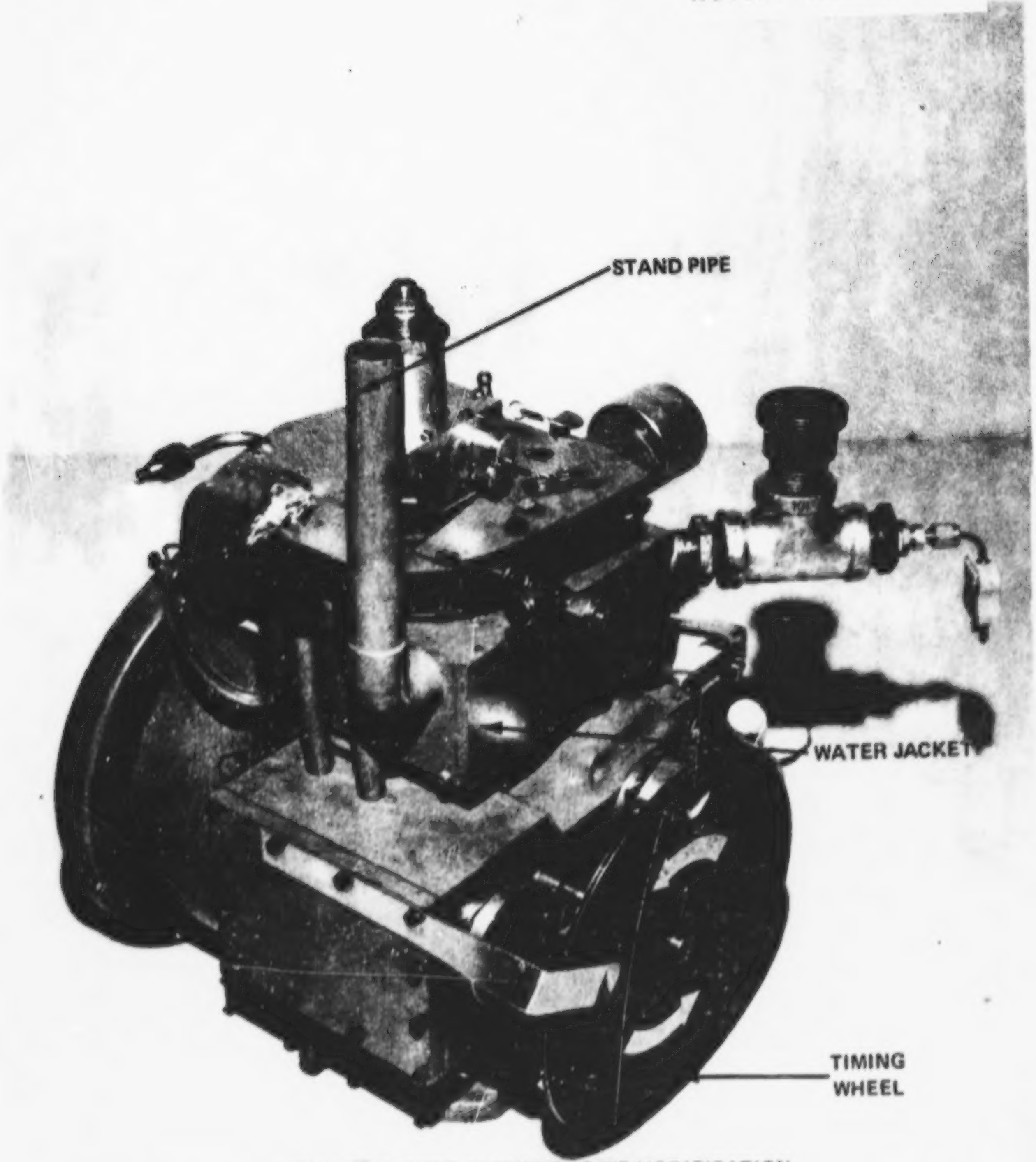

STAND PIPE
WATER JACKET
TIMING
WHEEL

FIGURE 25 WATER JACKET ENGINE MODIFICATION

Figure 26

TREE DIAGRAM-WATER JACKETED DATA RUNS

INJECTION TIMING	AIR FLOW % MAX	LOAD % MAX RATING AT RPM	RPM	RUN NO.	NOX GRAMS/ BHP-Hr
+35° to -25°	100%	35%	2000	710	2.0
			2500	711	1.1
			3000	712	1.3
			3500	713	1.5
			4000	714	1.6
		65%	2000	715	2.3
			2500	716	2.6
			3000	717	2.4
			3500	718	2.3
			4000	719	2.1
		100%	2000	720	2.8
			2500	721	2.3
			3000	722	2.2
			3500	723	2.1
			4000	724	2.5
	80%	35%	2000	725	2.4
			2500	726	1.2
			3000	727	1.3
			3500	728	1.3
			4000	729	1.5
		65%	2000	730	2.6
			2500	731	1.8
			3000	732	1.8
			3500	733	1.9
			4000	734	2.2
		100%	2000	735	3.0
			2500	736	1.8
			3000	737	1.1
			3500	738	1.3
			4000	739	1.7
	70%	35%	2000	742	2.2
			2500	743	0.9
			3000	744	1.0
			3500	745	1.2
			4000	746	1.0
		65%	2000	747	1.9
			2500	748	1.6
			3000	749	1.5
			3500	750	1.6
			4000	751	1.7
		100%	2000	752	2.6
			2500	753	1.9
			3000	754	1.4
			3500	755	1.3
			4000	756	1.8

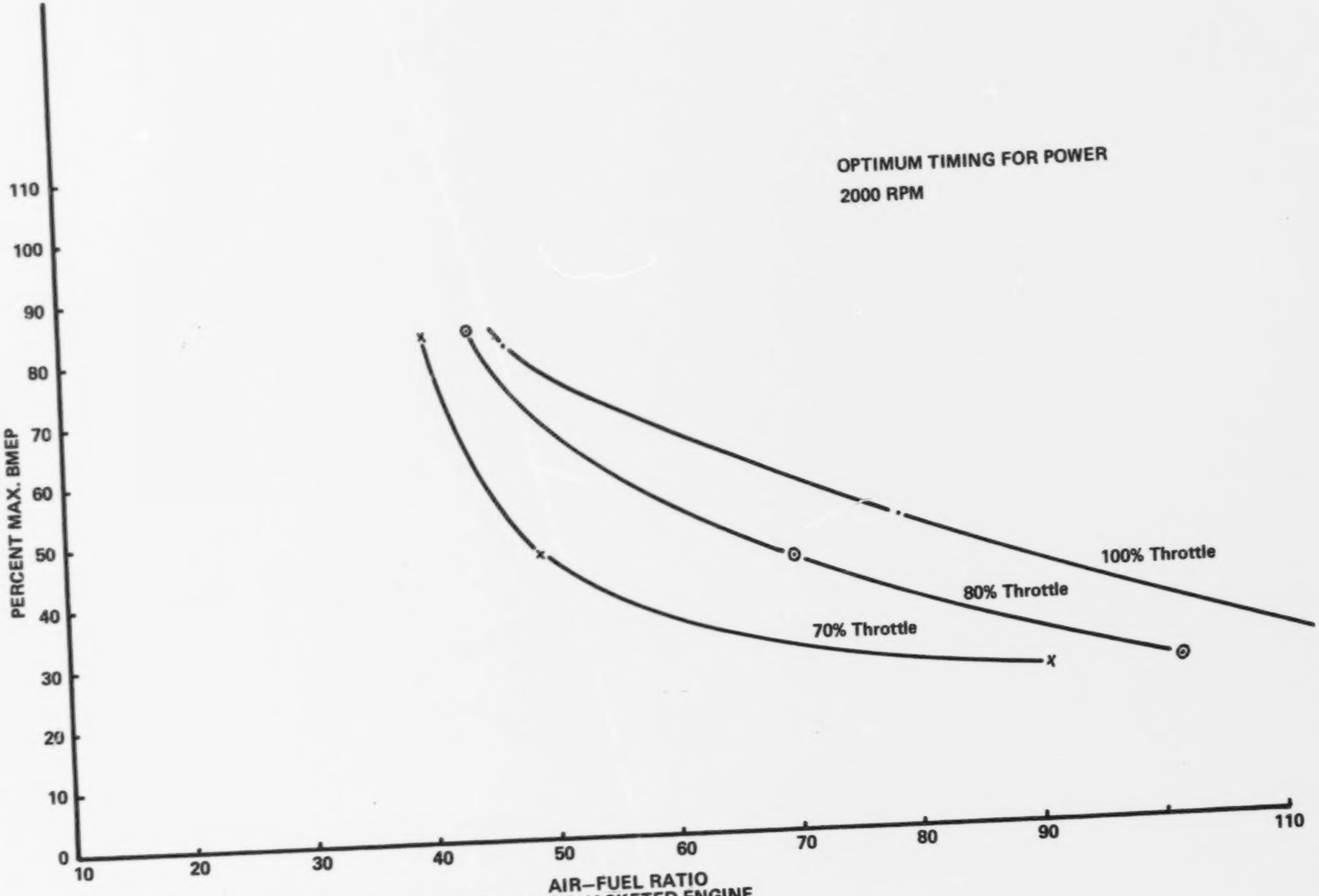


FIGURE 27A POWER–MIXTURE RELATIONSHIPS – WATER JACKETED ENGINE

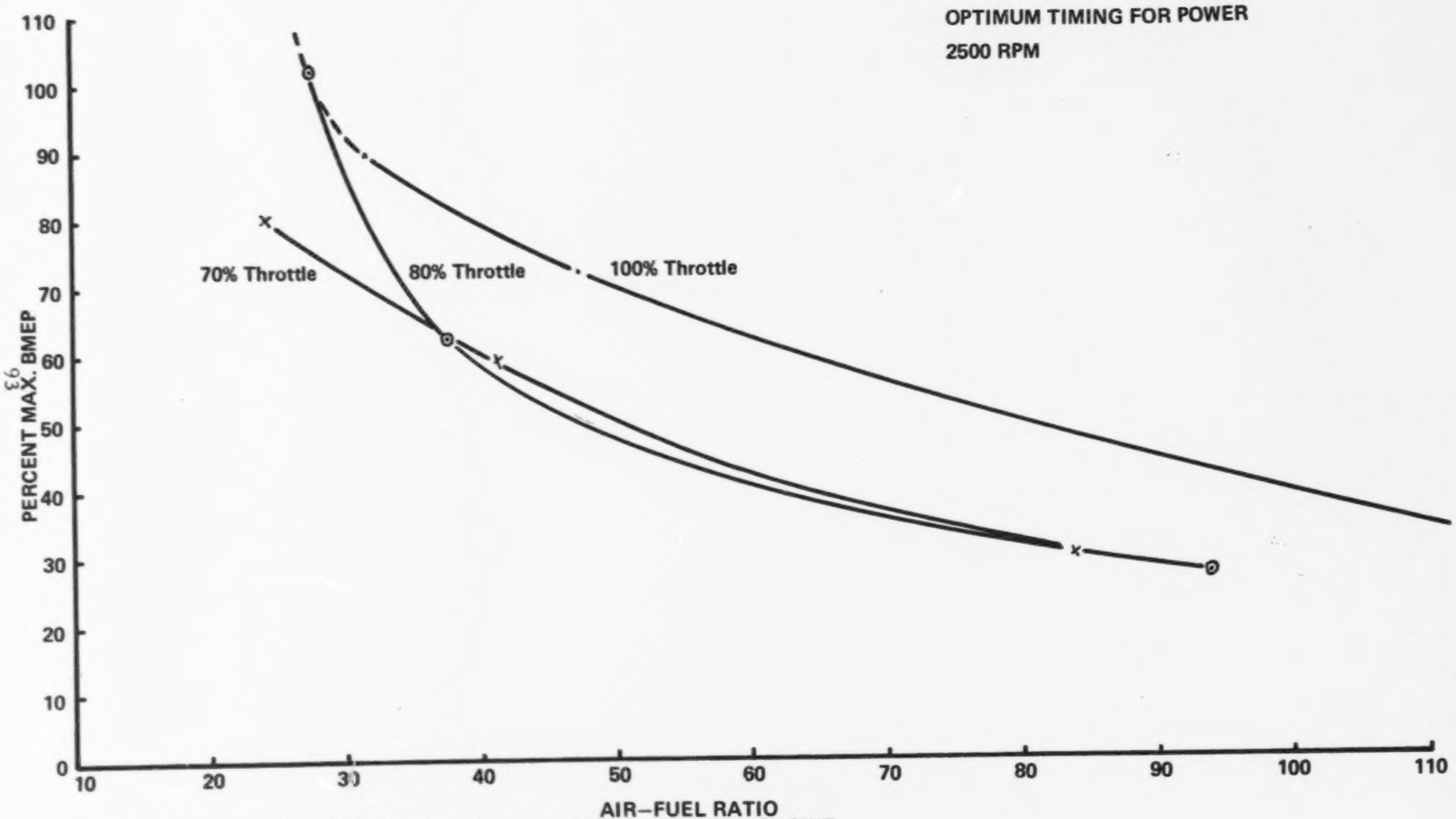


FIGURE 27B POWER–MIXTURE RELATIONSHIPS – WATER JACKETED ENGINE

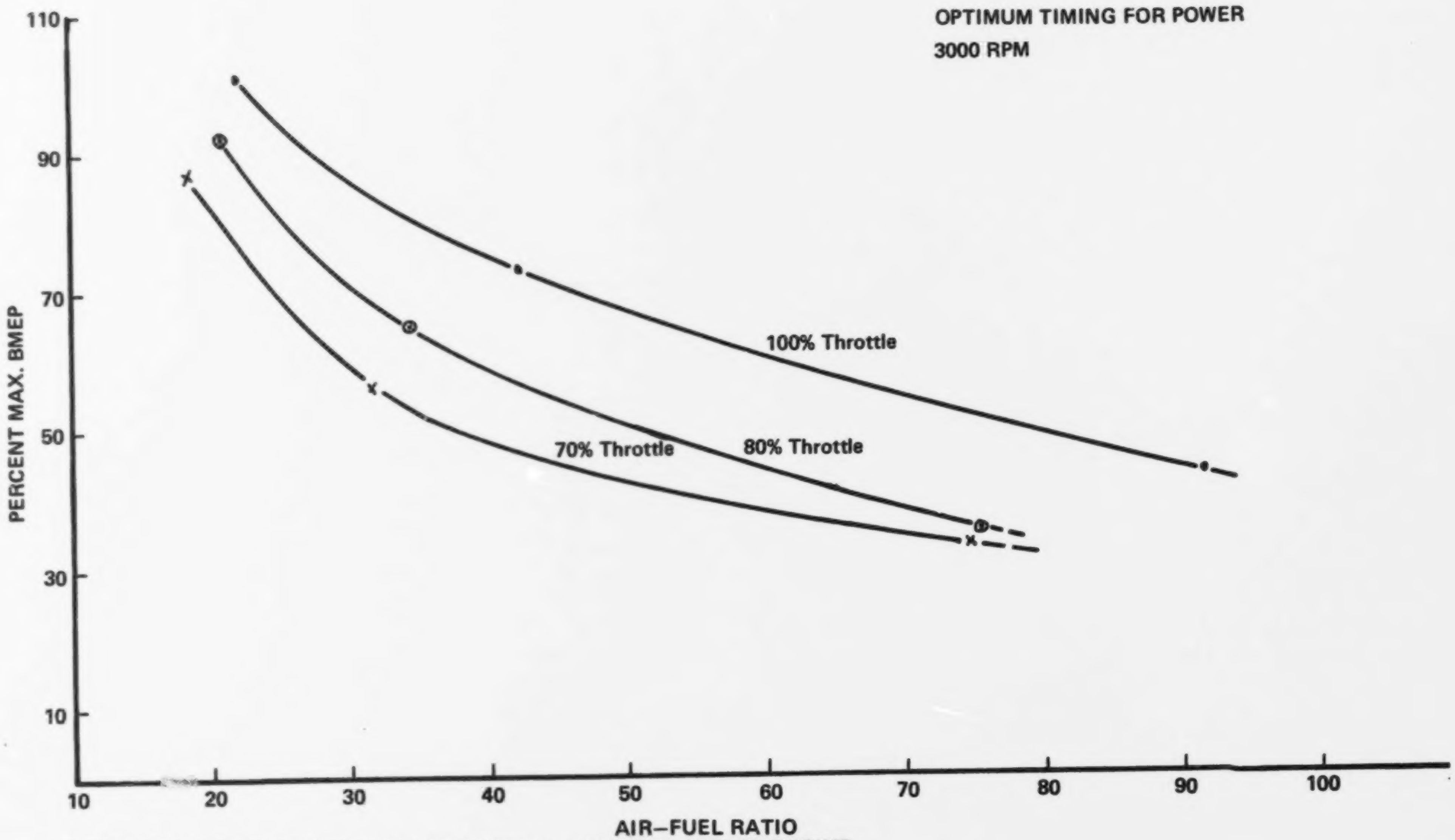


FIGURE 27C POWER–MIXTURE RELATIONSHIPS – WATER JACKETED ENGINE

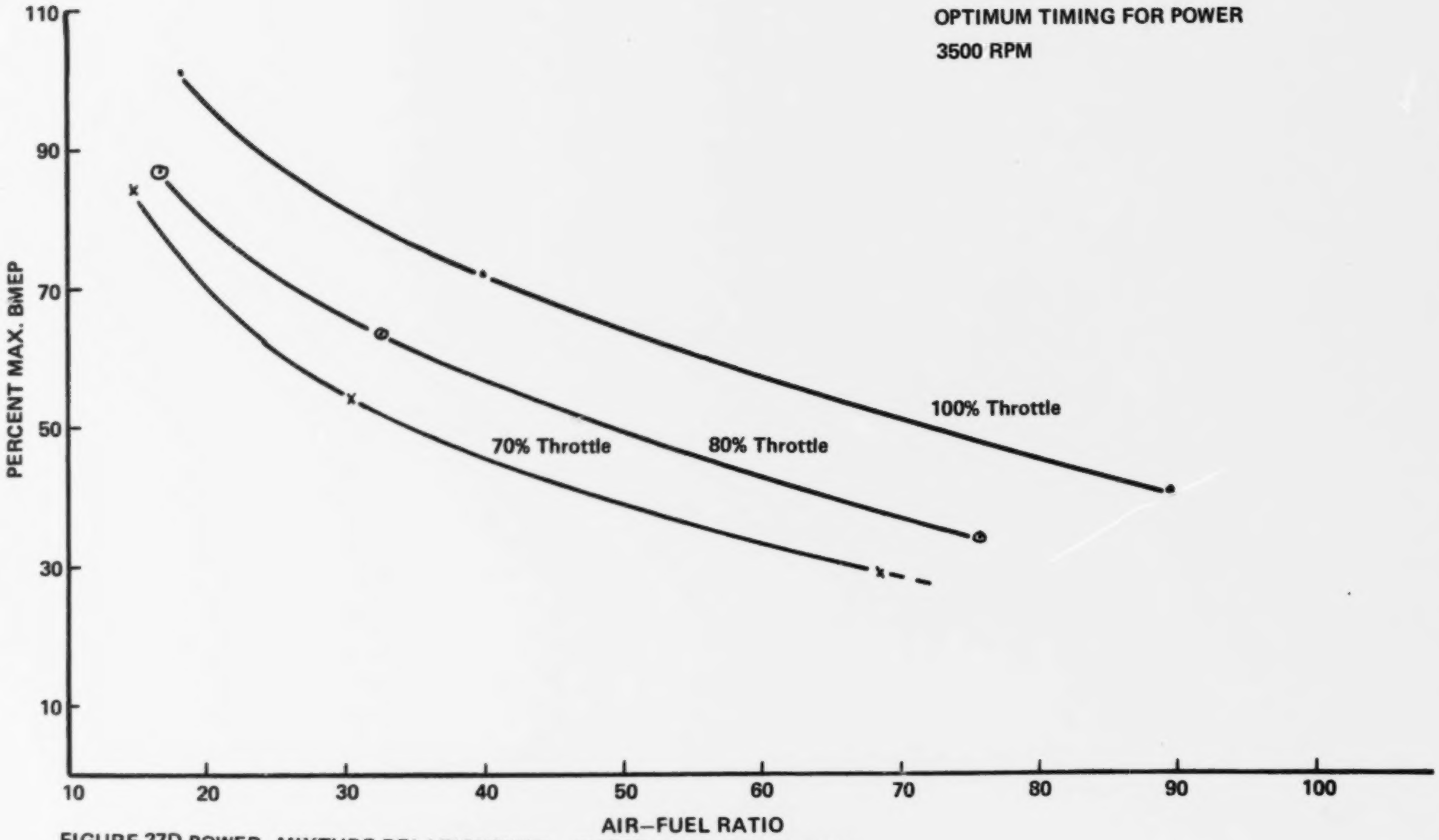


FIGURE 27D POWER–MIXTURE RELATIONSHIPS – WATER JACKETED ENGINE

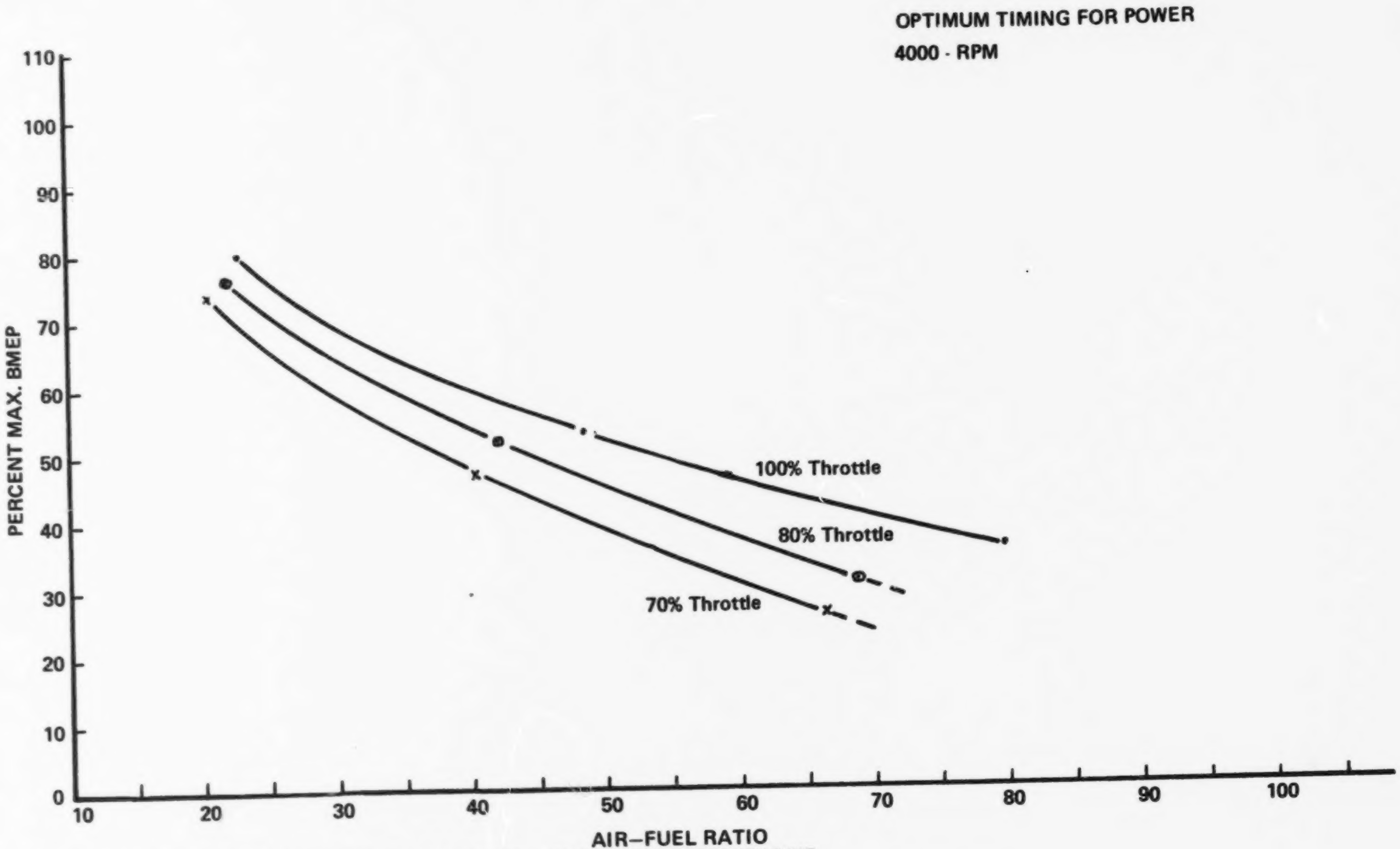


FIGURE 27E POWER—MIXTURE RELATIONSHIPS — WATER JACKETED ENGINE

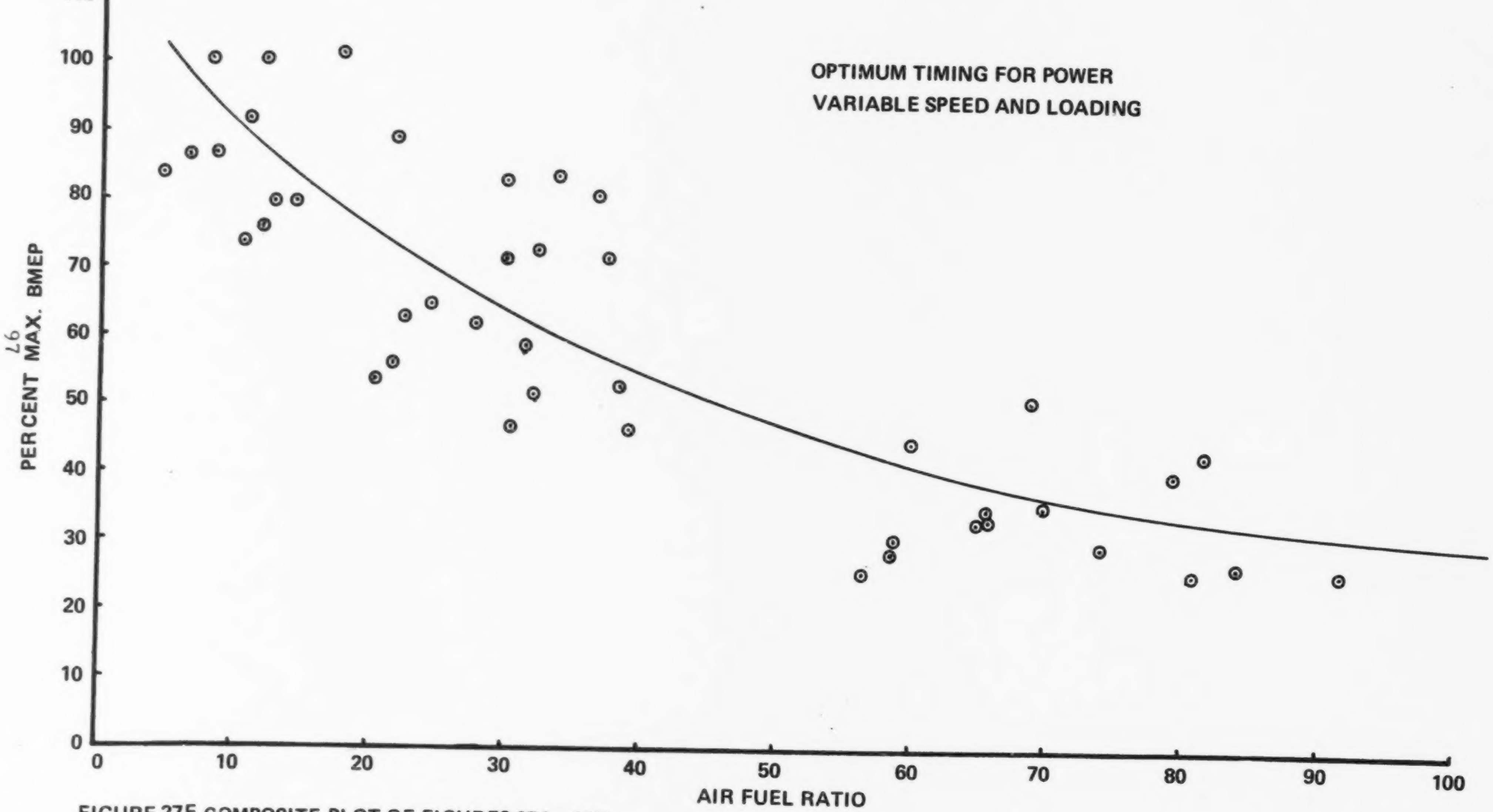
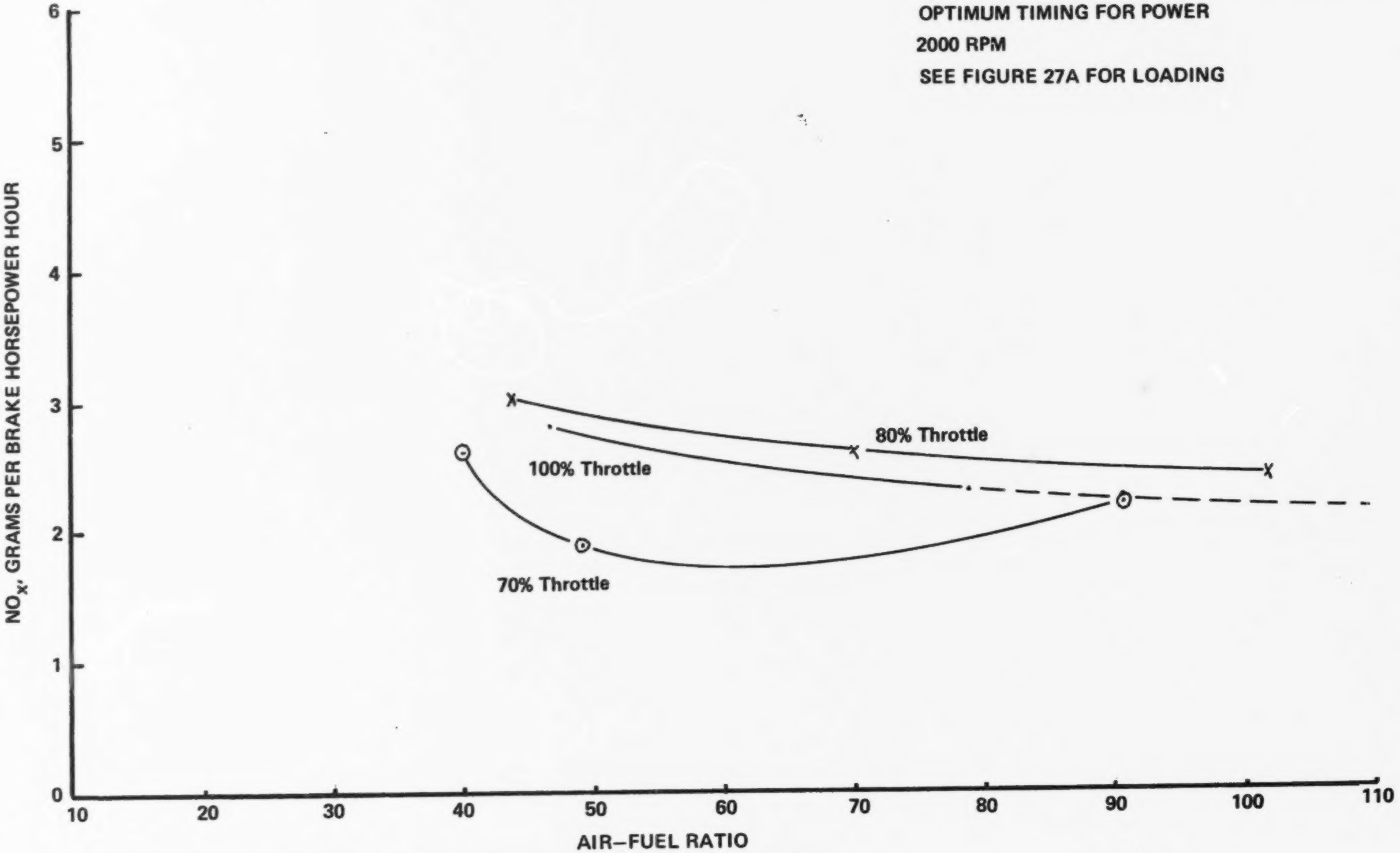


FIGURE 27F COMPOSITE PLOT OF FIGURES 27A–27E



OPTIMUM TIMING FOR POWER
2000 RPM
SEE FIGURE 27A FOR LOADING

FIGURE 28A EMISSION–MIXTURE RELATIONSHIPS – WATER JACKETED ENGINE

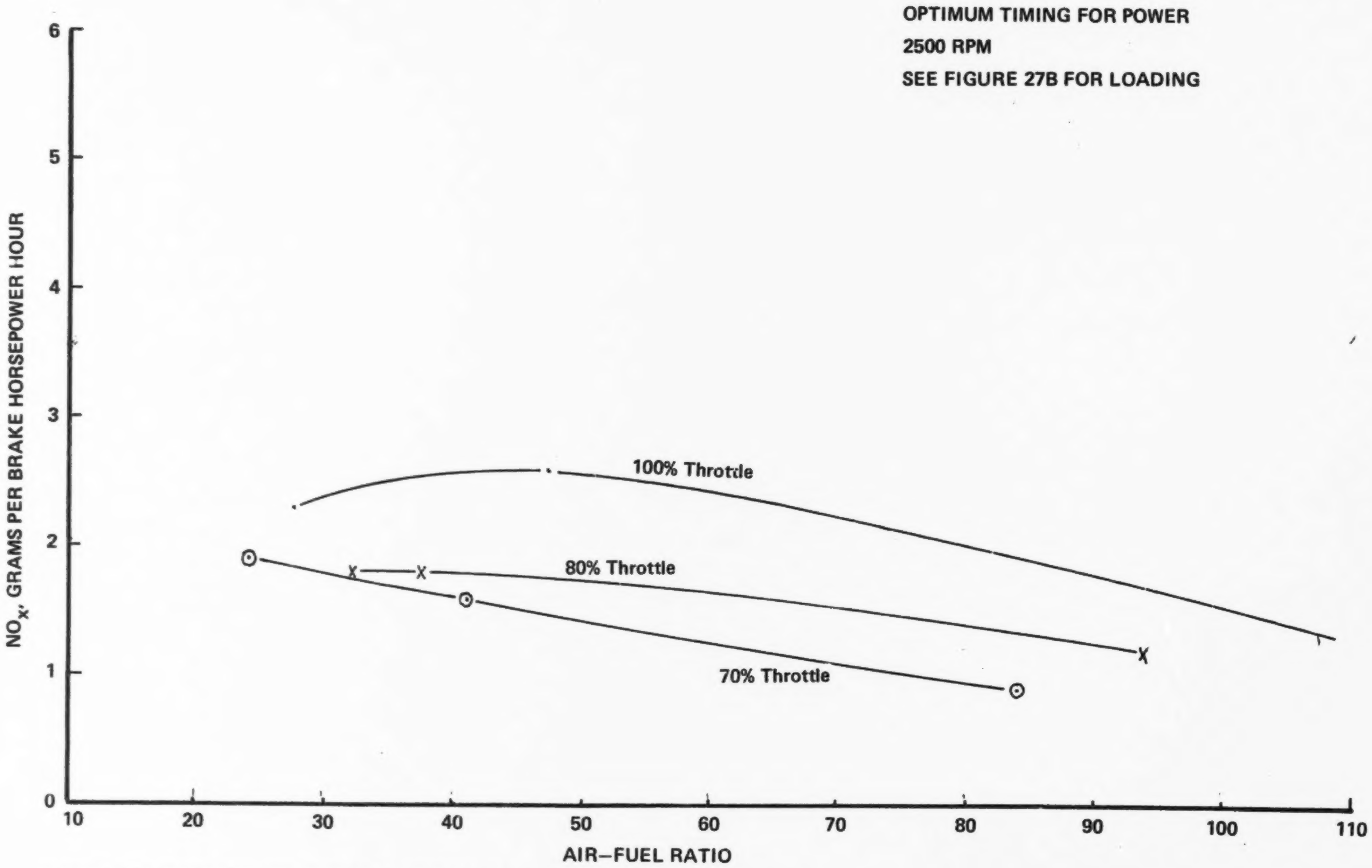
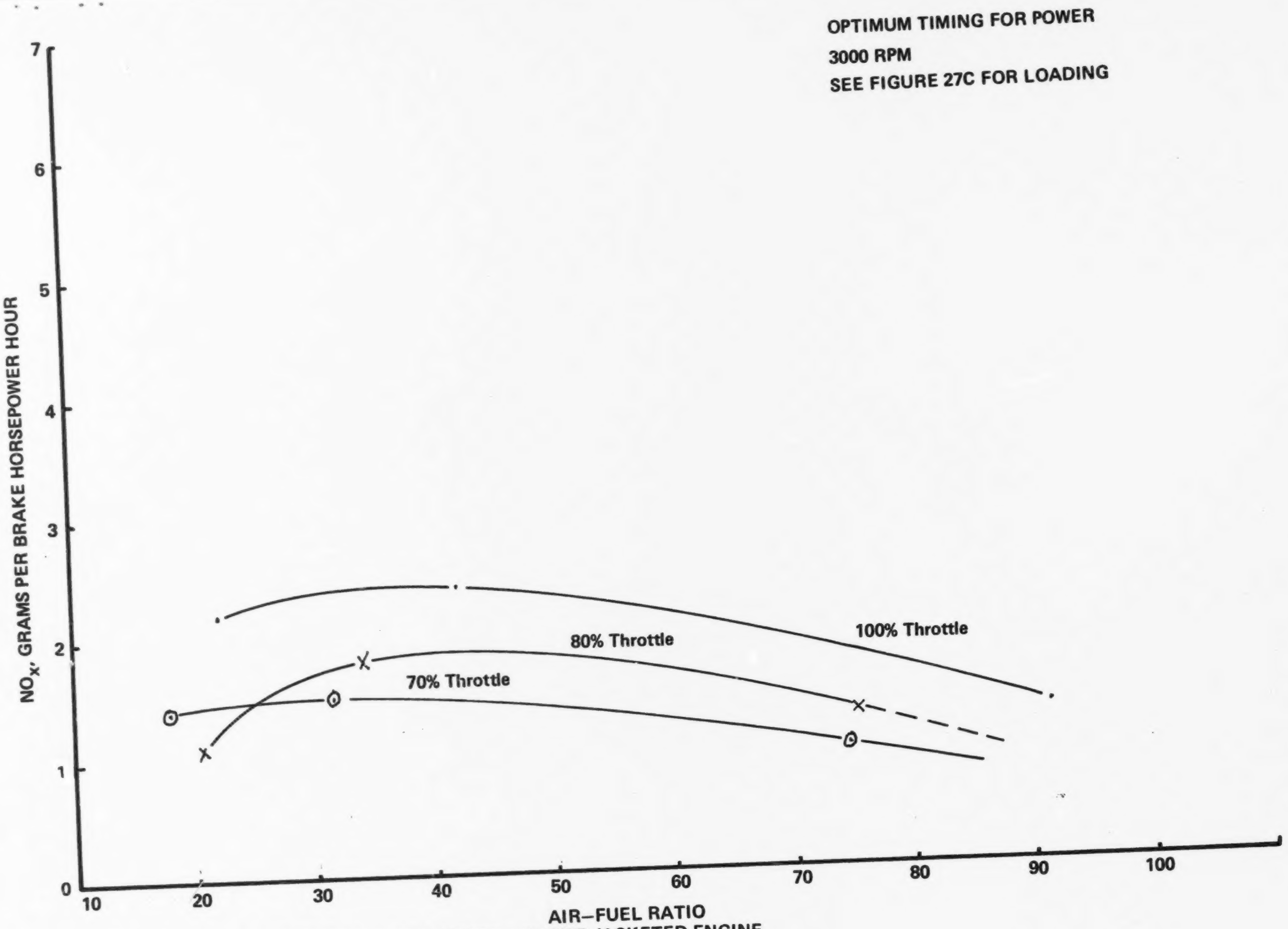
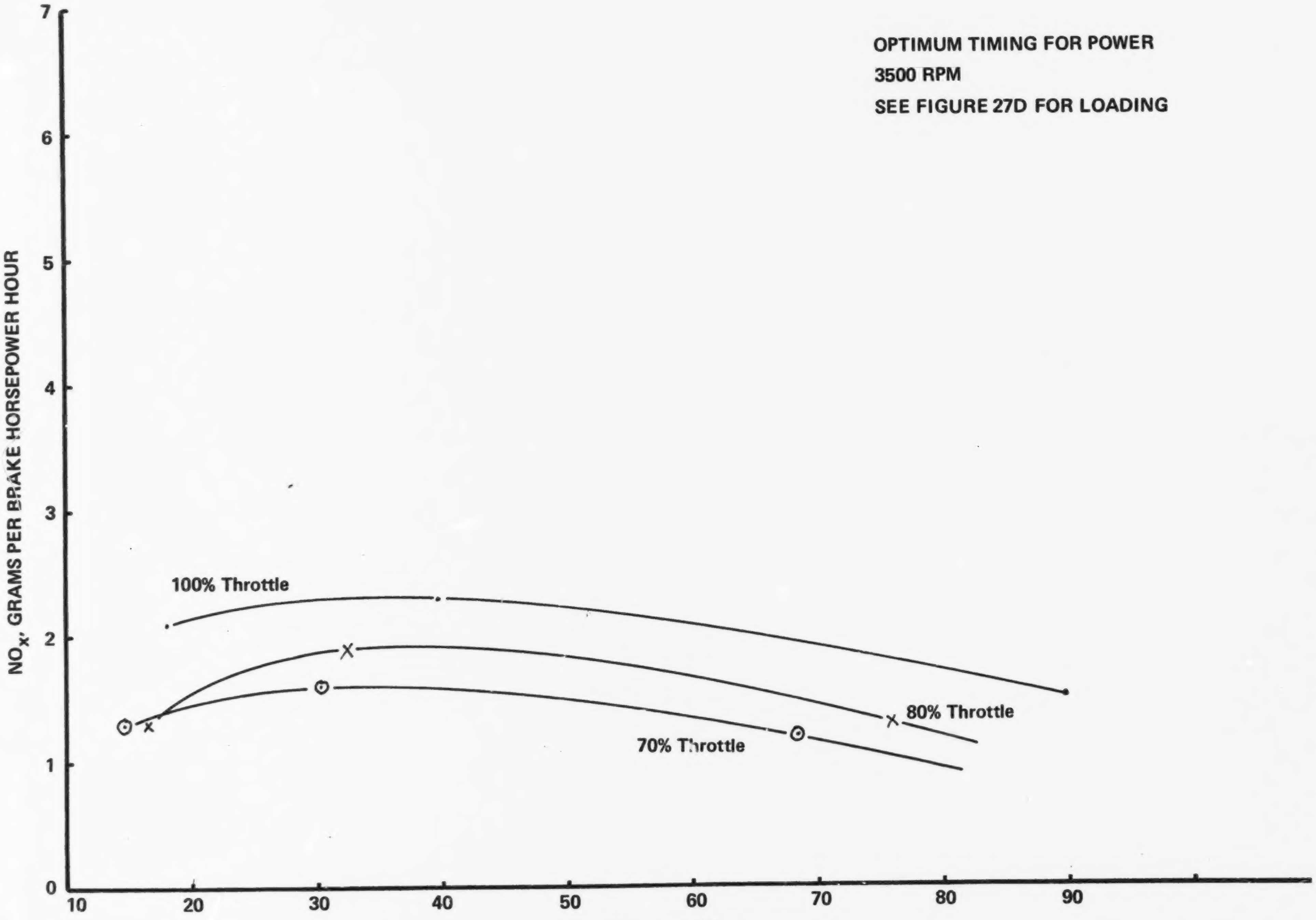


FIGURE 28B EMISSION–MIXTURE RELATIONSHIPS – WATER JACKETED ENGINE



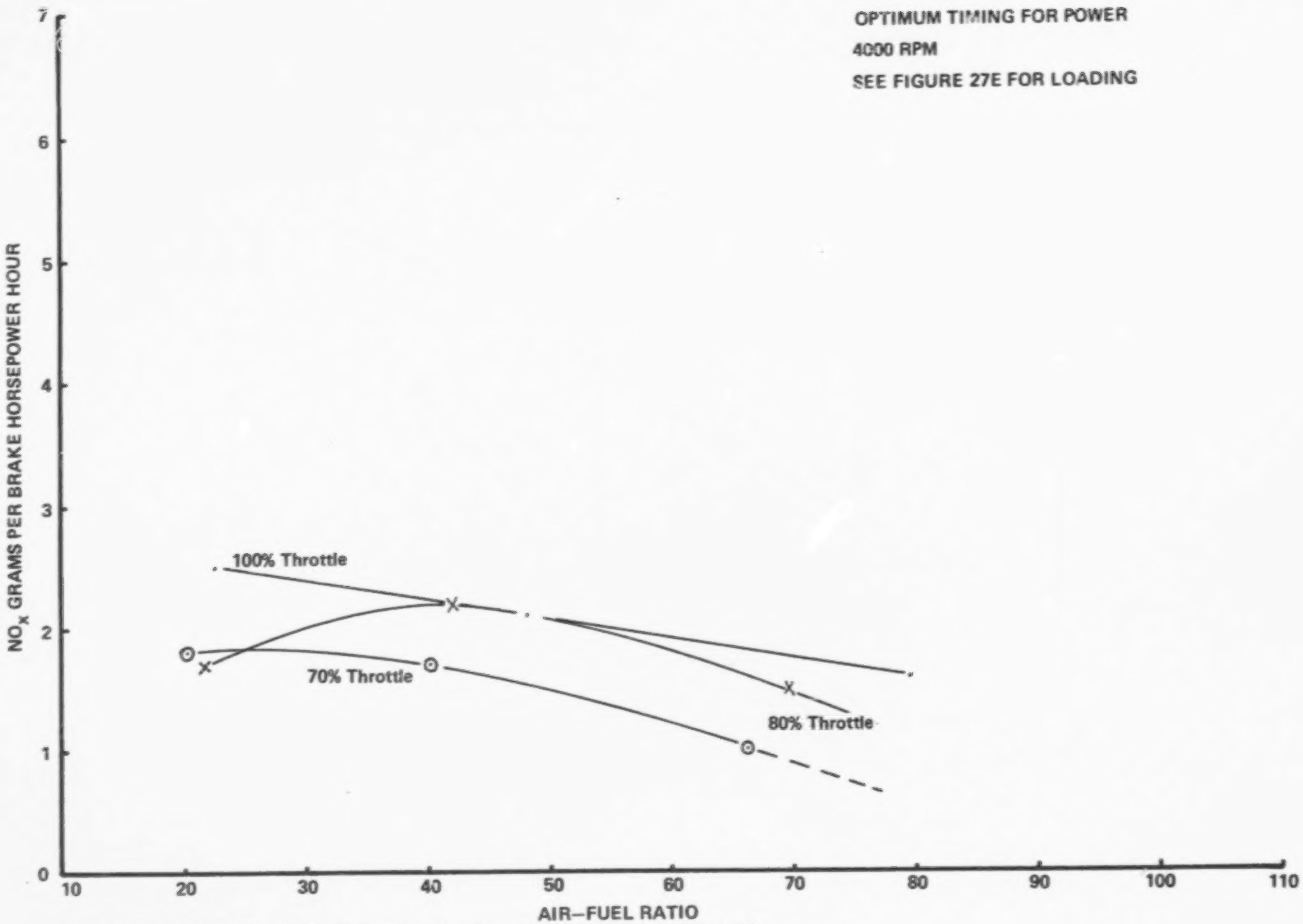
OPTIMUM TIMING FOR POWER
3000 RPM
SEE FIGURE 27C FOR LOADING

FIGURE 28C EMISSION–MIXTURE RELATIONSHIPS – WATER JACKETED ENGINE



OPTIMUM TIMING FOR POWER
3500 RPM
SEE FIGURE 27D FOR LOADING

FIGURE 28D EMISSION–MIXTURE RELATIONSHIPS – WATER JACKETED ENGINE



OPTIMUM TIMING FOR POWER

4000 RPM

SEE FIGURE 27E FOR LOADING

FIGURE 28E EMISSION–MIXTURE RELATIONSHIPS – WATER JACKETED ENGINE

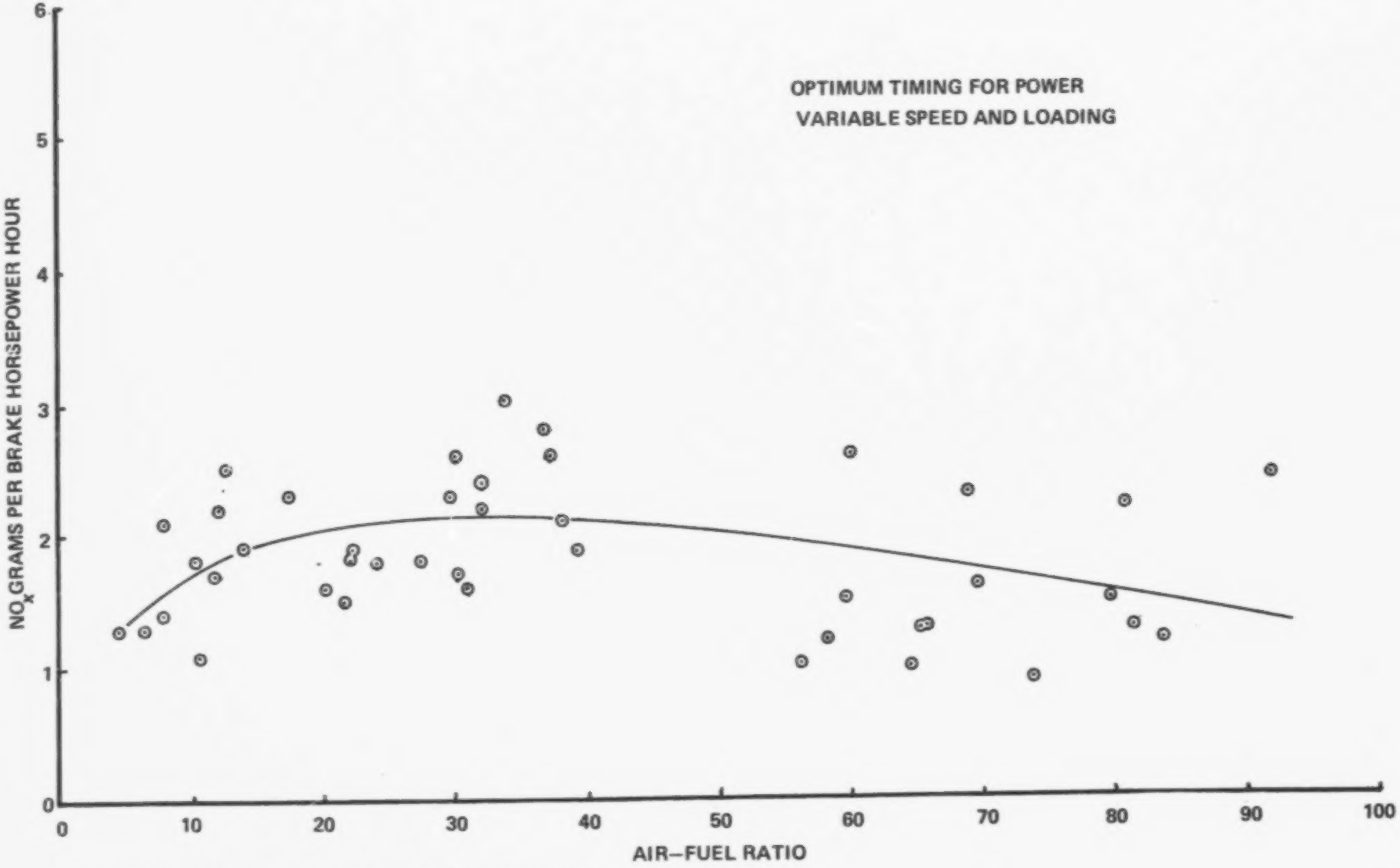
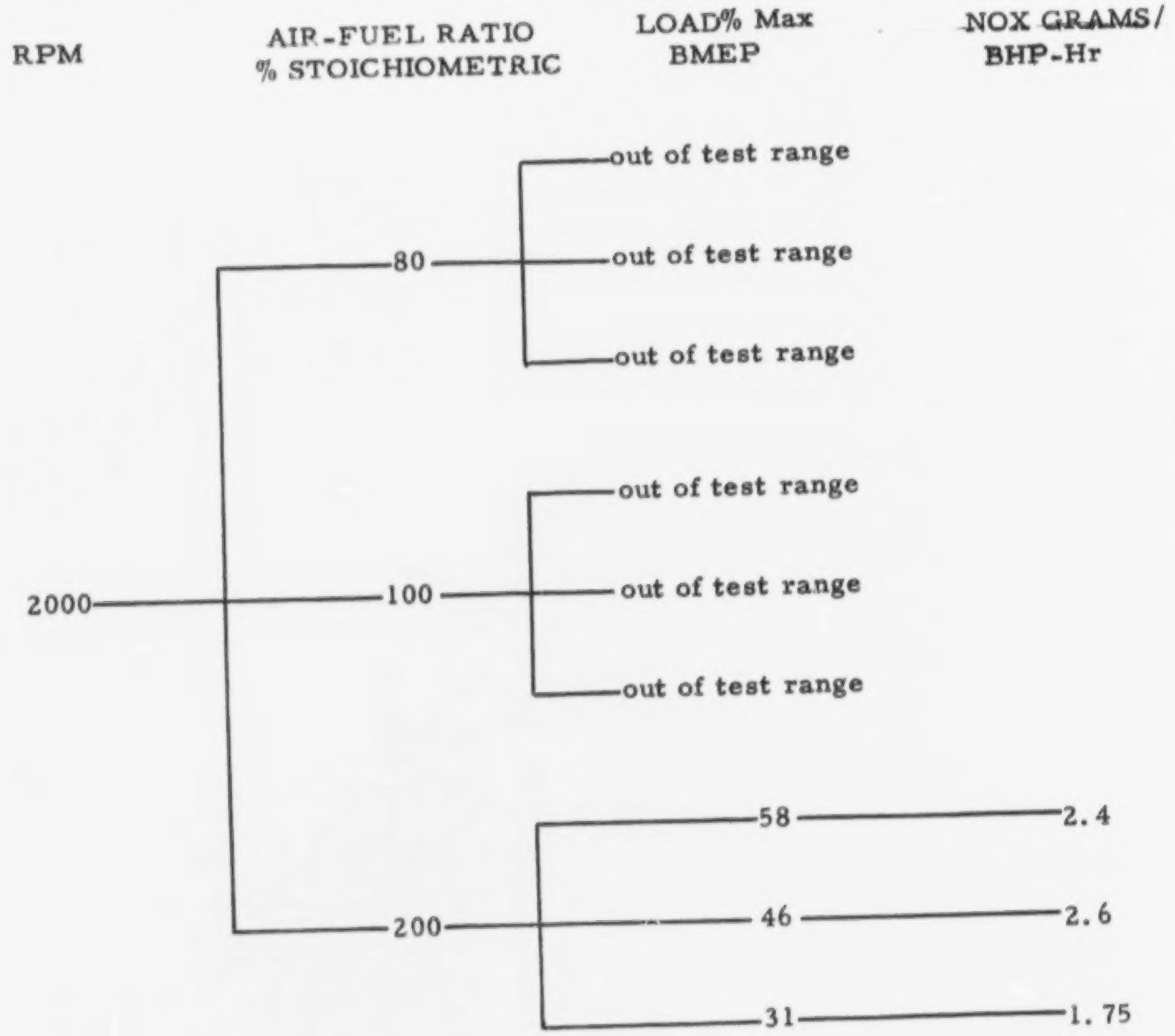


FIGURE 28F COMPOSITE PLOT OF FIGURES 28A–28E

Figure 29A

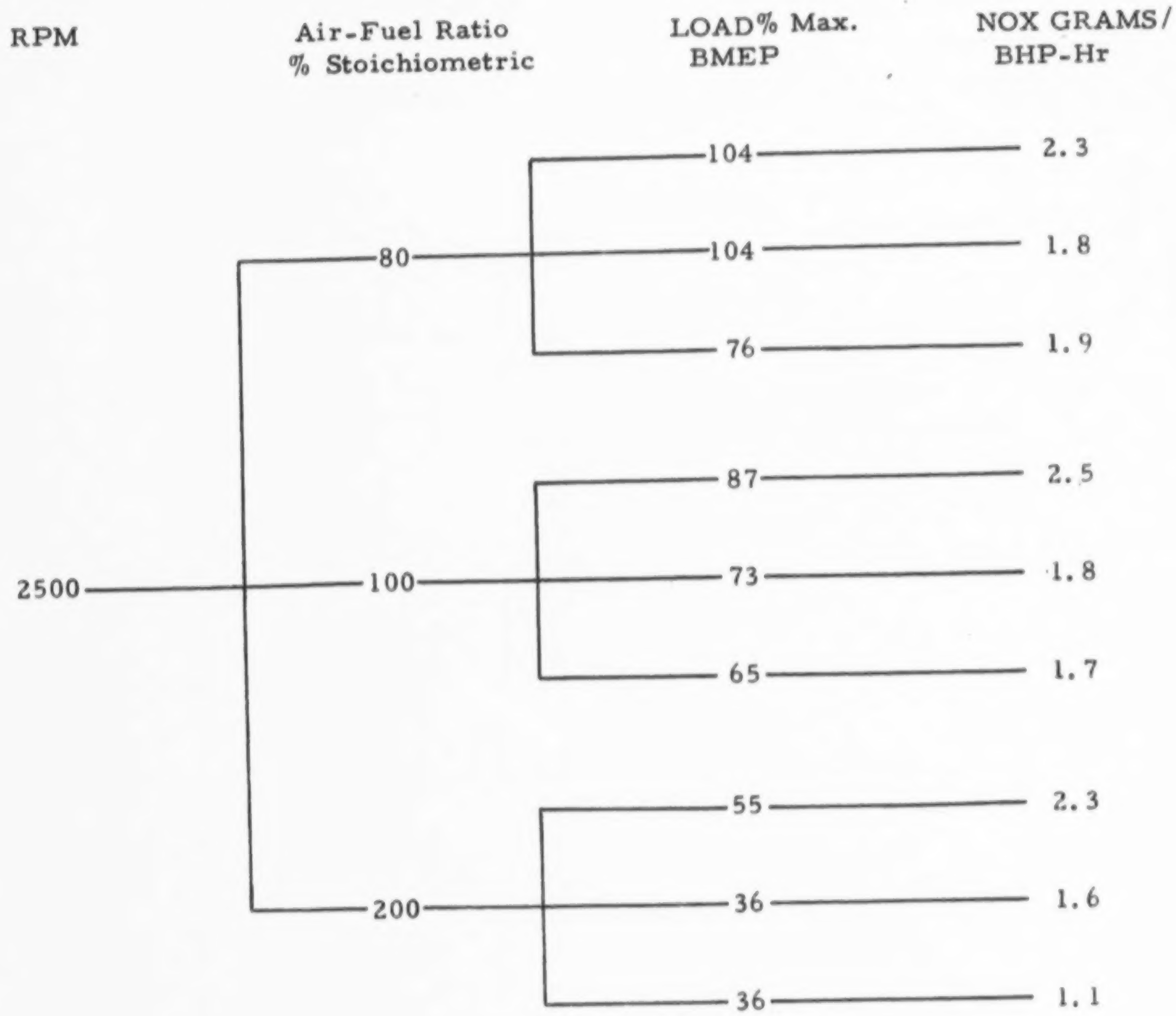
TREE DIAGRAM--WATER JACKETED ENGINE EMISSIONS-- OAP FORMAT


RPM
AIR-FUEL RATIO % STOICHIOMETRIC
LOAD% Max BMEP
NOX GRAMS/ BHP-Hr
2000
80
out of test range
out of test range
out of test range
100
out of test range
out of test range
out of test range
200
58
2.4
46
2.6
31
1.75

OPTIMUM TIMING

Figure 29B

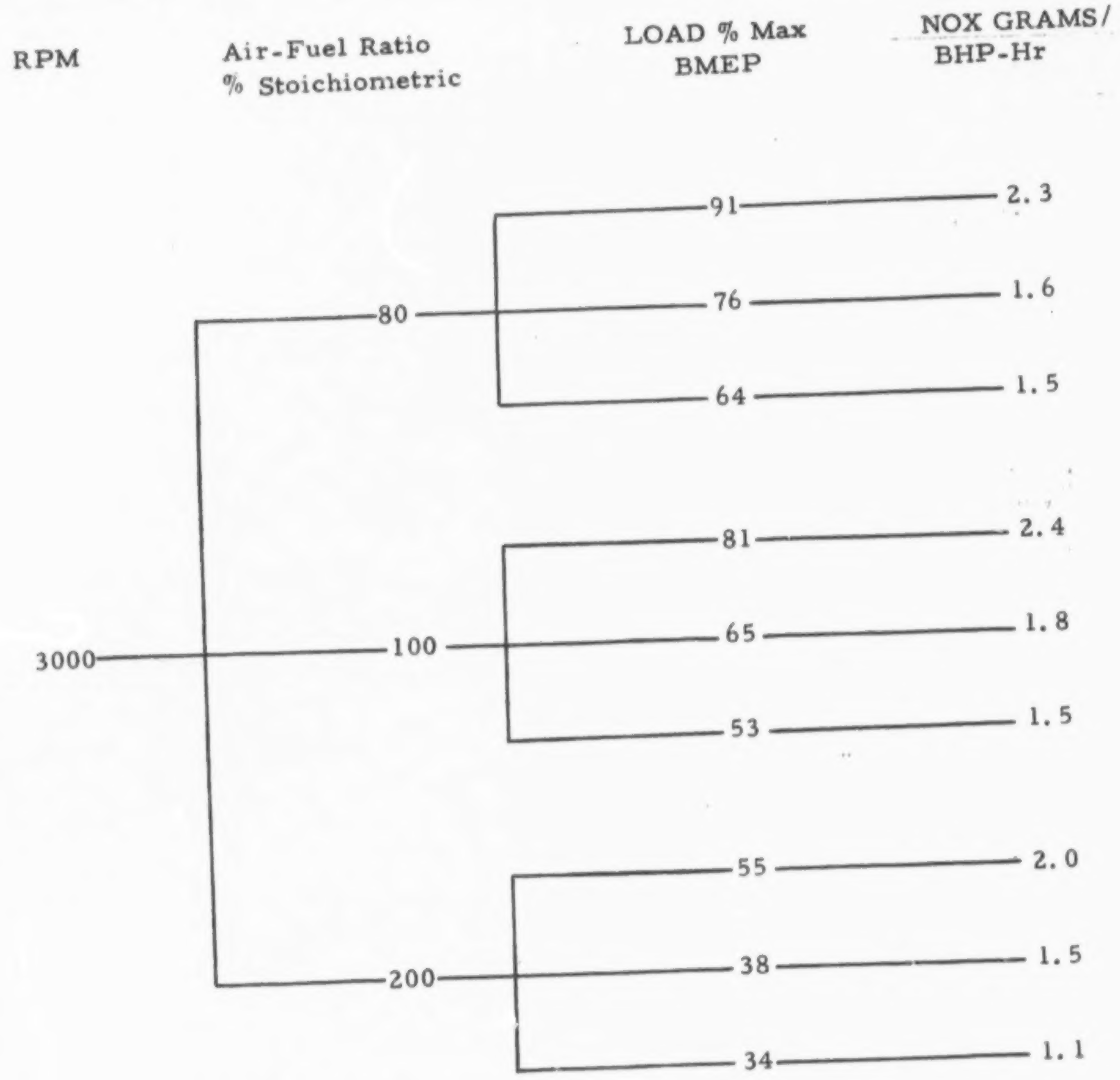
TREE DIAGRAM--WATER JACKETED ENGINE EMISSIONS-- OAP FORMAT


RPM
Air-Fuel Ratio % Stoichiometric
LOAD% Max. BMEP
NOX GRAMS/ BHP-Hr
2500
80
100
200
104
104
76
87
73
65
55
36
36
2.3
1.8
1.9
2.5
1.8
1.7
2.3
1.6
1.1

OPTIMUM TIMING

Figure 29C

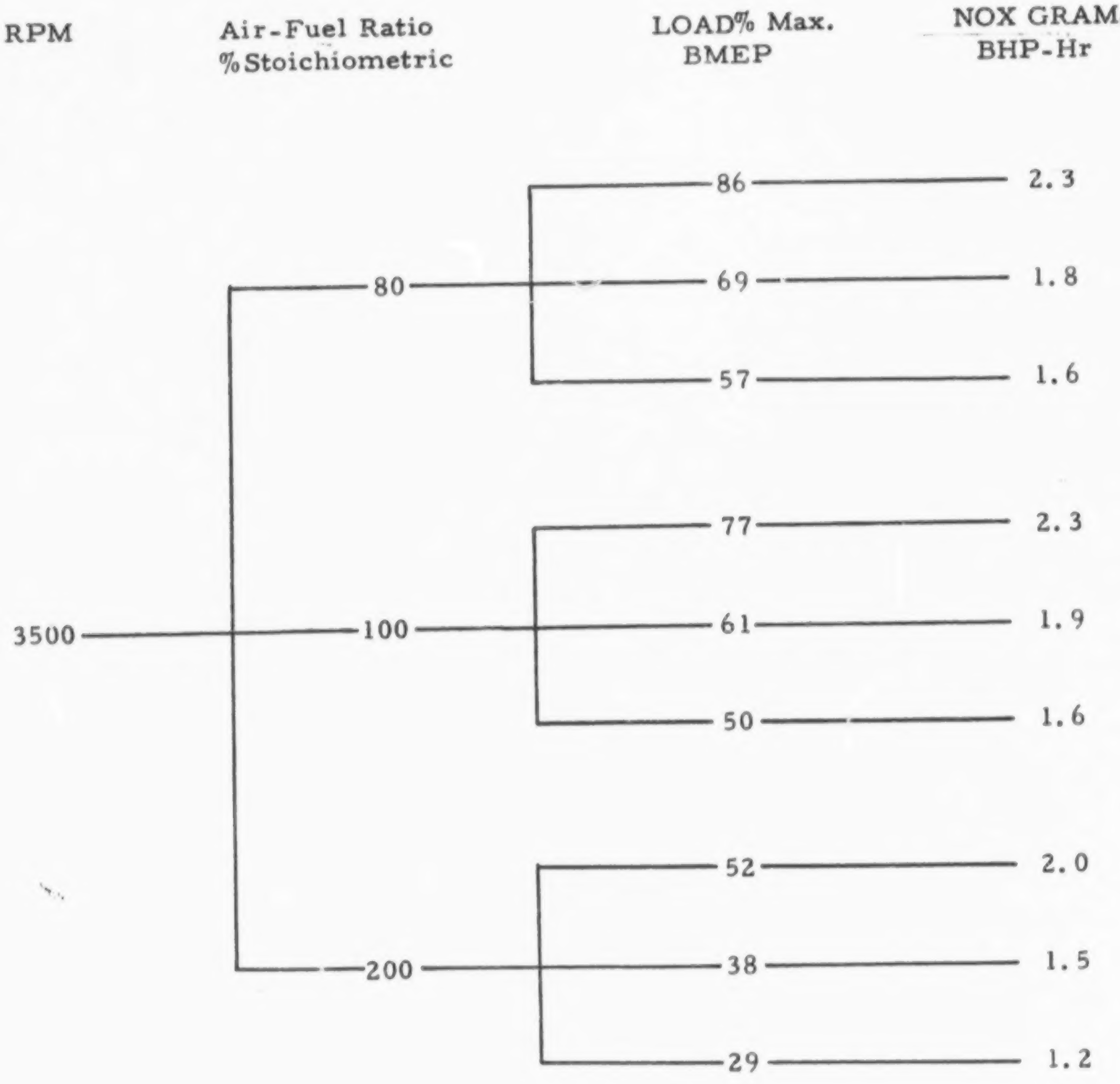
TREE DIAGRAM--WATER JACKETED ENGINE EMISSIONS-- OAP FORMAT


RPM
Air-Fuel Ratio % Stoichiometric
LOAD % Max BMEP
NOX GRAMS/ BHP-Hr
3000
80
100
200
91
76
64
81
65
53
55
38
34
2.3
1.6
1.5
2.4
1.8
1.5
2.0
1.5
1.1

OPTIMUM TIMING

Figure 29D

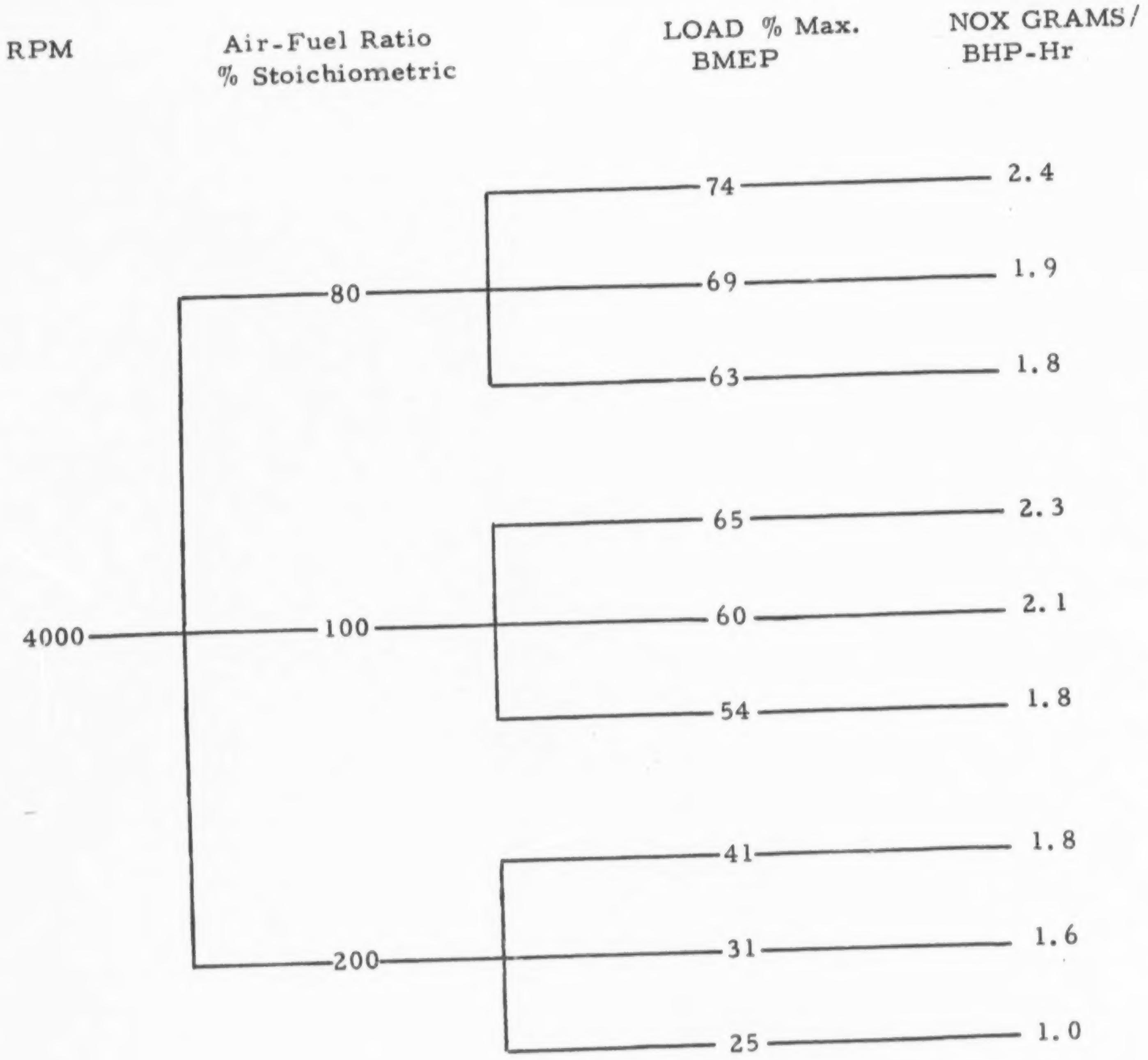
TREE DIAGRAM--WATER JACKETED ENGINE EMISSIONS-- OAP FORMAT


RPM
Air-Fuel Ratio %Stoichiometric
LOAD% Max. BMEP
NOX GRAMS/ BHP-Hr
3500
80
100
200
86
69
57
77
61
50
52
38
29
2.3
1.8
1.6
2.3
1.9
1.6
2.0
1.5
1.2

OPTIMUM TIMING

Figure 29E

TREE DIAGRAM--WATER JACKETED ENGINE EMISSIONS-- OAP FORMAT


RPM
Air-Fuel Ratio % Stoichiometric
LOAD % Max. BMEP
NOX GRAMS/ BHP-Hr
4000
80
100
200
74
69
63
65
60
54
41
31
25
2.4
1.9
1.8
2.3
2.1
1.8
1.8
1.6
1.0

OPTIMUM TIMING

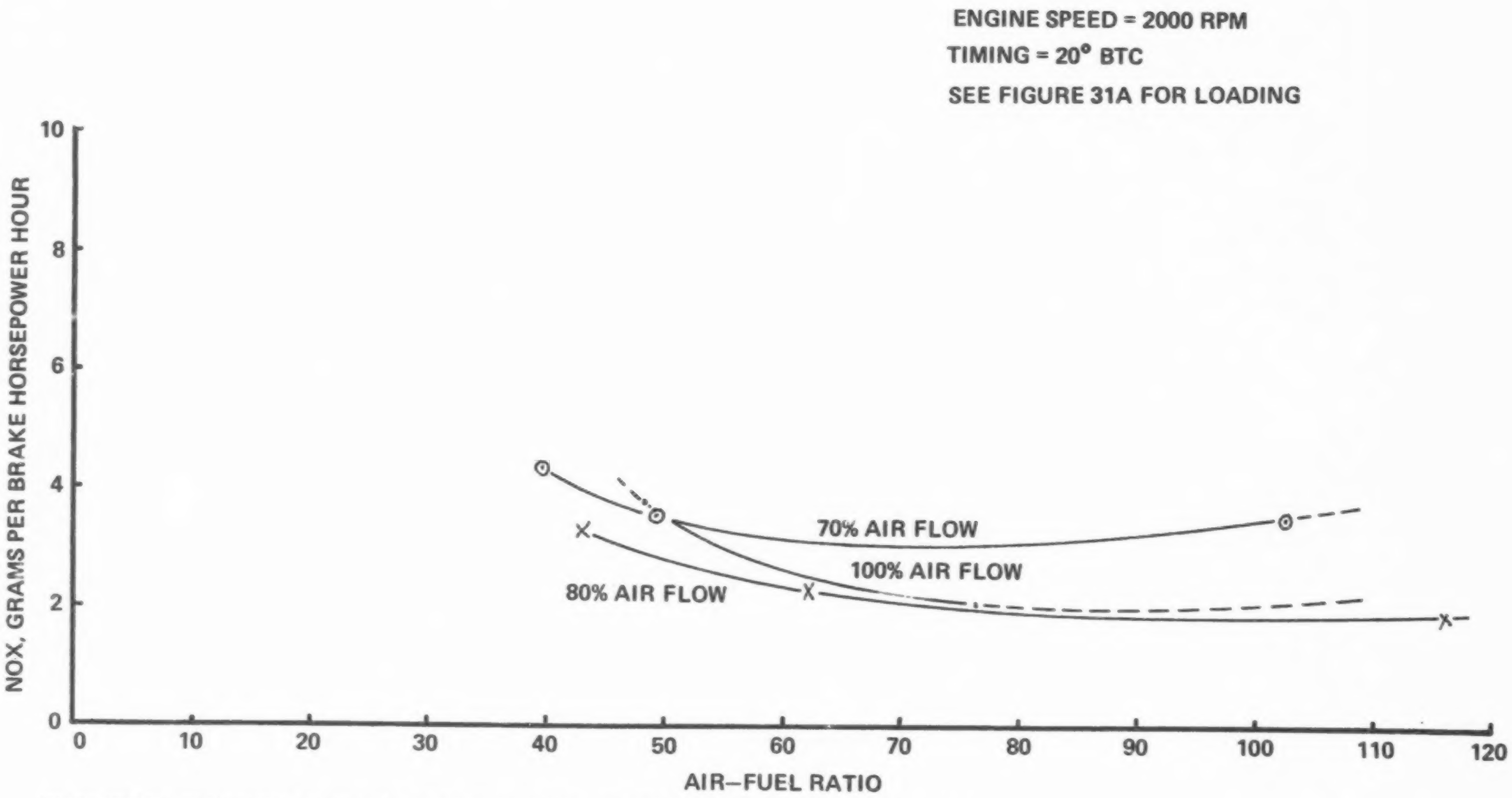


FIGURE 30A EMISSION-MIXTURE RELATIONSHIP - ADVANCED COMBINATION ANGLE

ENGINE SPEED = 2500 RPM
TIMING = 20° BTC
SEE FIGURE 31B FOR LOADING

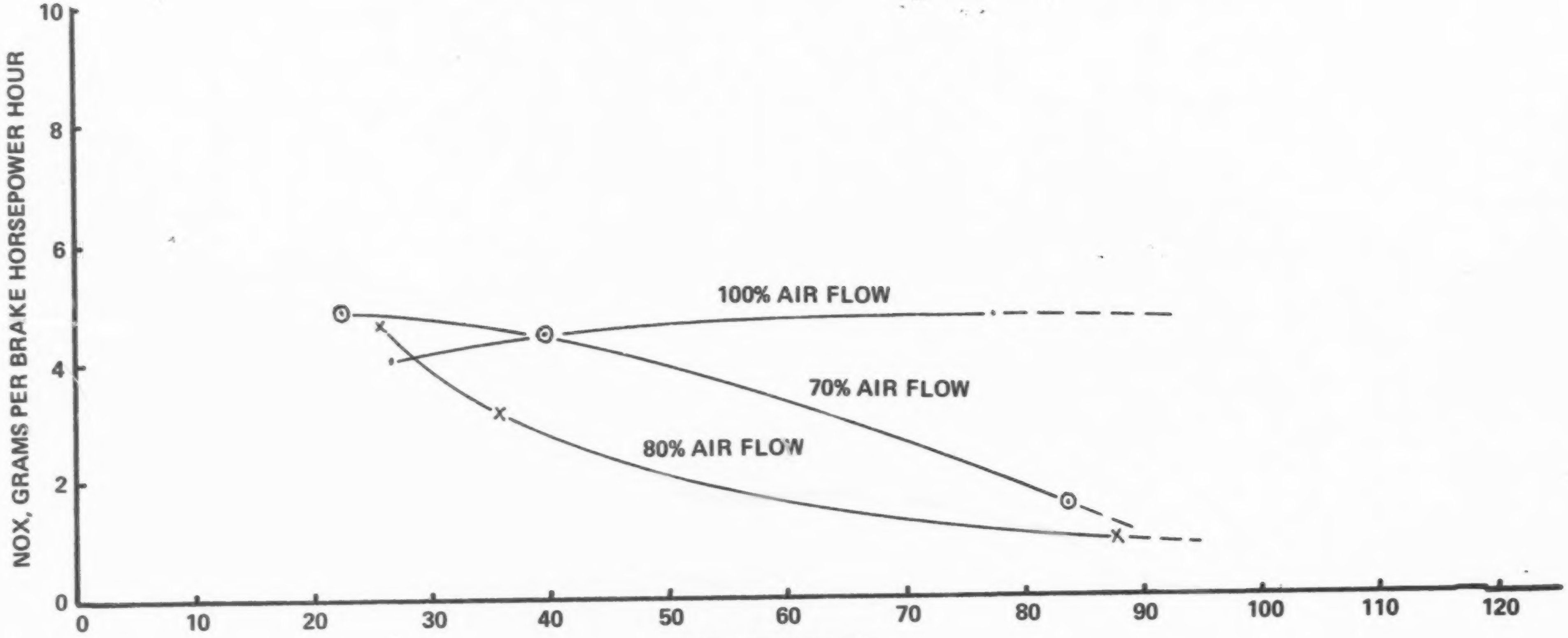


FIGURE 30B EMISSION-MIXTURE RELATIONSHIP - ADVANCED COMBINATION ANGLE

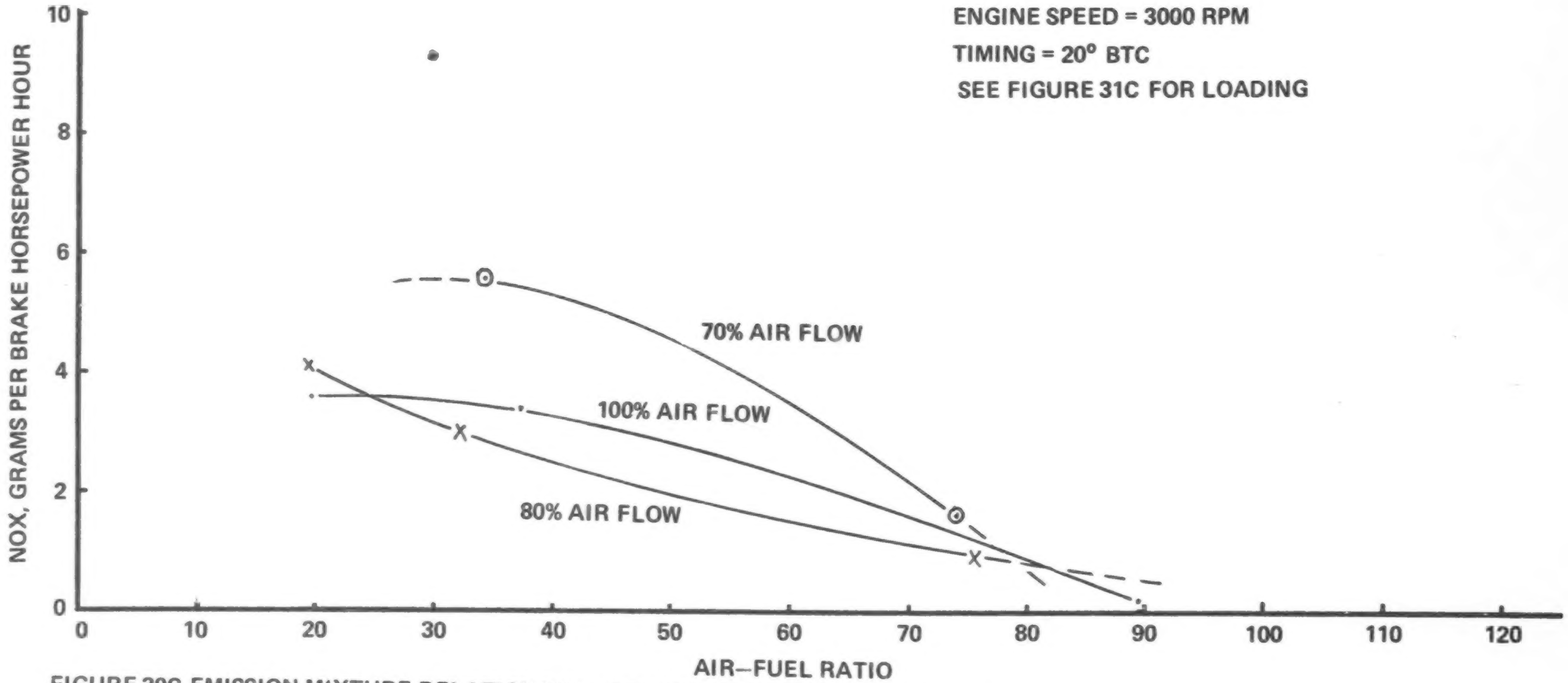
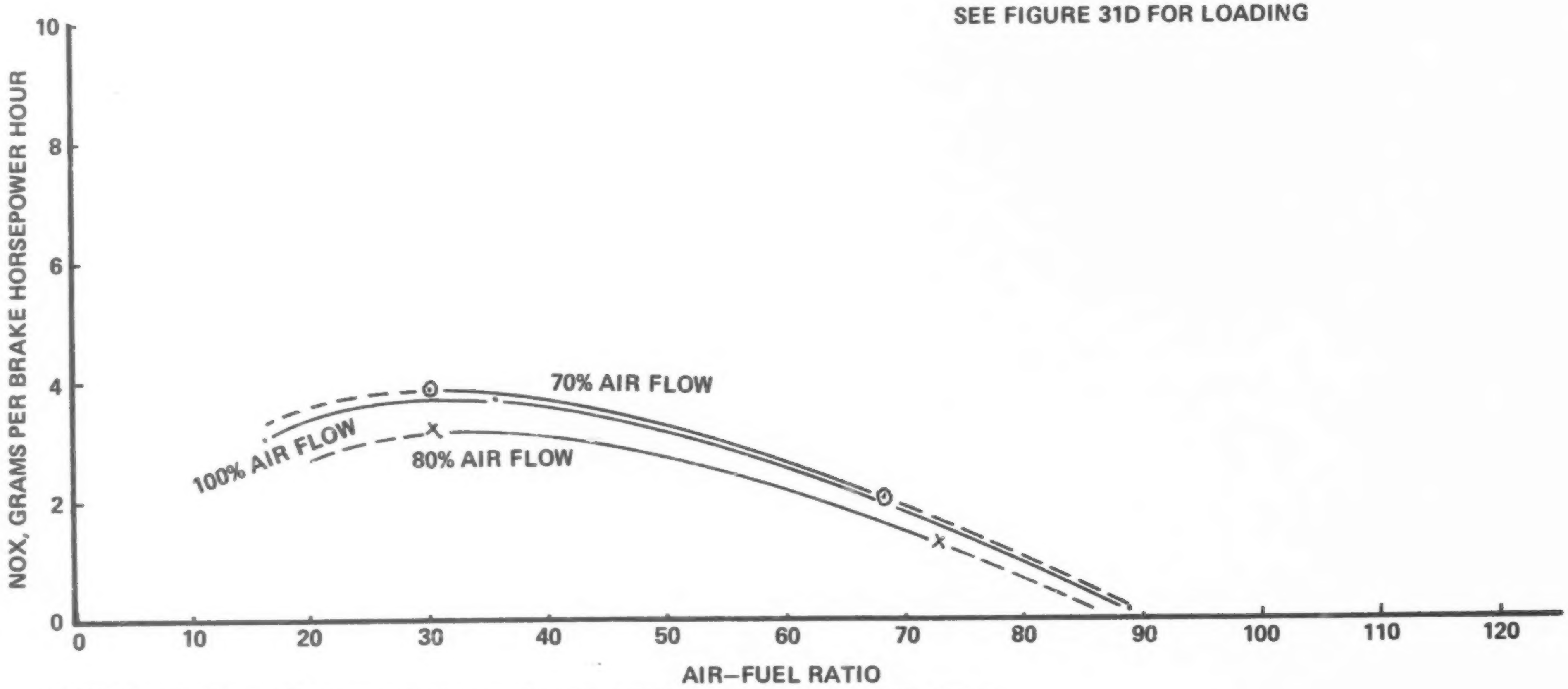


FIGURE 30C EMISSION-MIXTURE RELATIONSHIP - ADVANCED COMBINATION ANGLE



ENGINE SPEED = 3500 RPM
TIMING = 20° BTC
SEE FIGURE 31D FOR LOADING

FIGURE 30D EMISSION-MIXTURE RELATIONSHIP - ADVANCED COMBINATION ANGLE

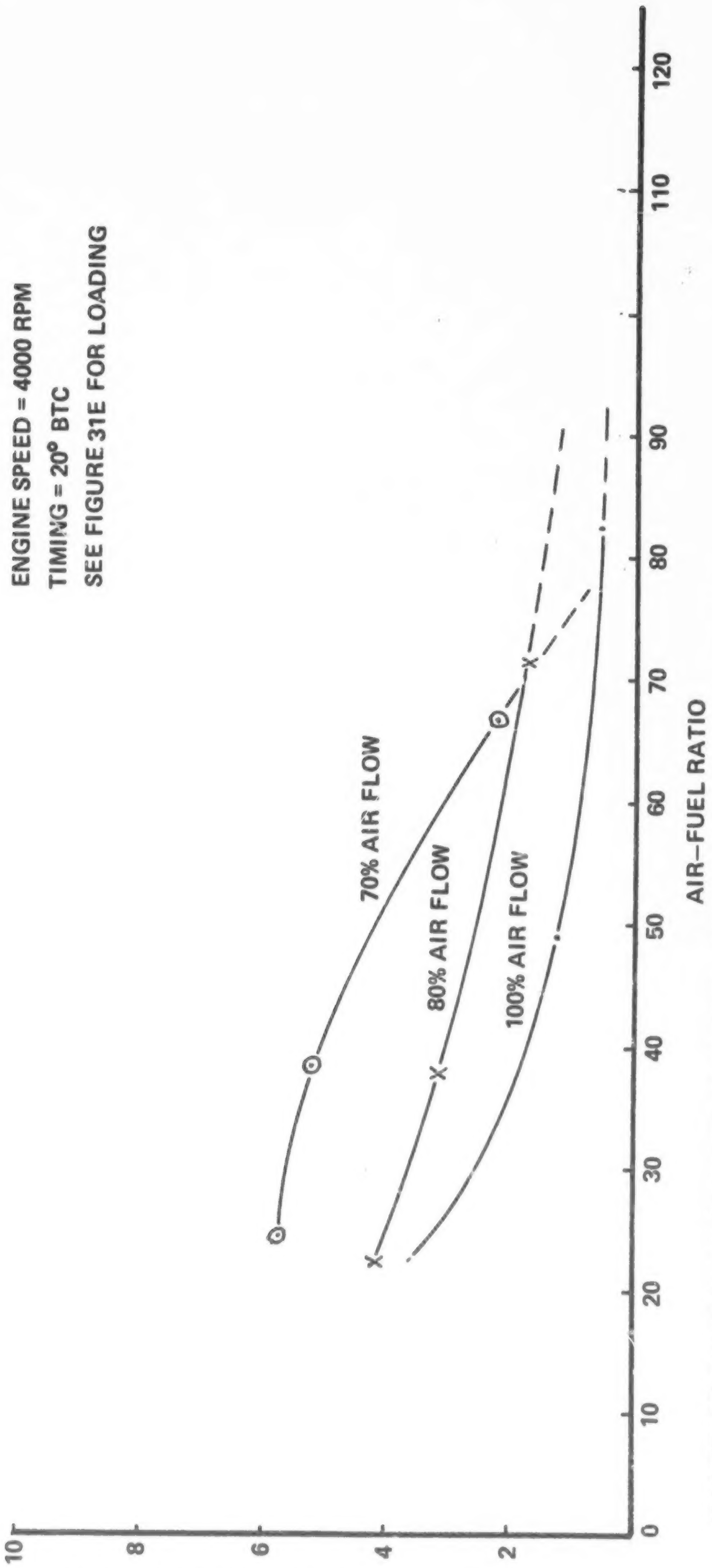


FIGURE 30E EMISSION-MIXTURE RELATIONSHIP - ADVANCED COMBINATION ANGLE

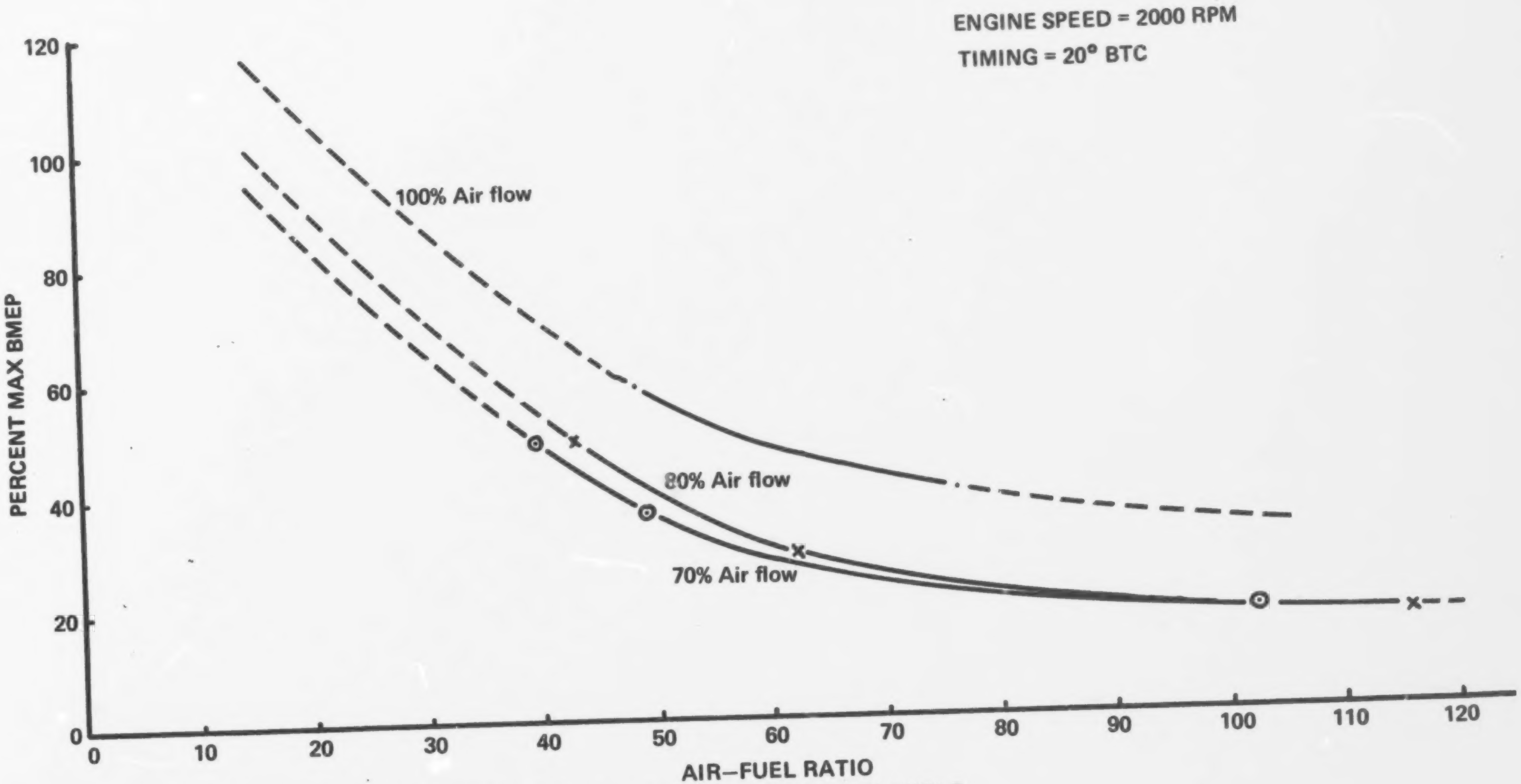


FIGURE 31A POWER–MIXTURE RELATIONSHIP – ADVANCED COMBINATION ANGLE

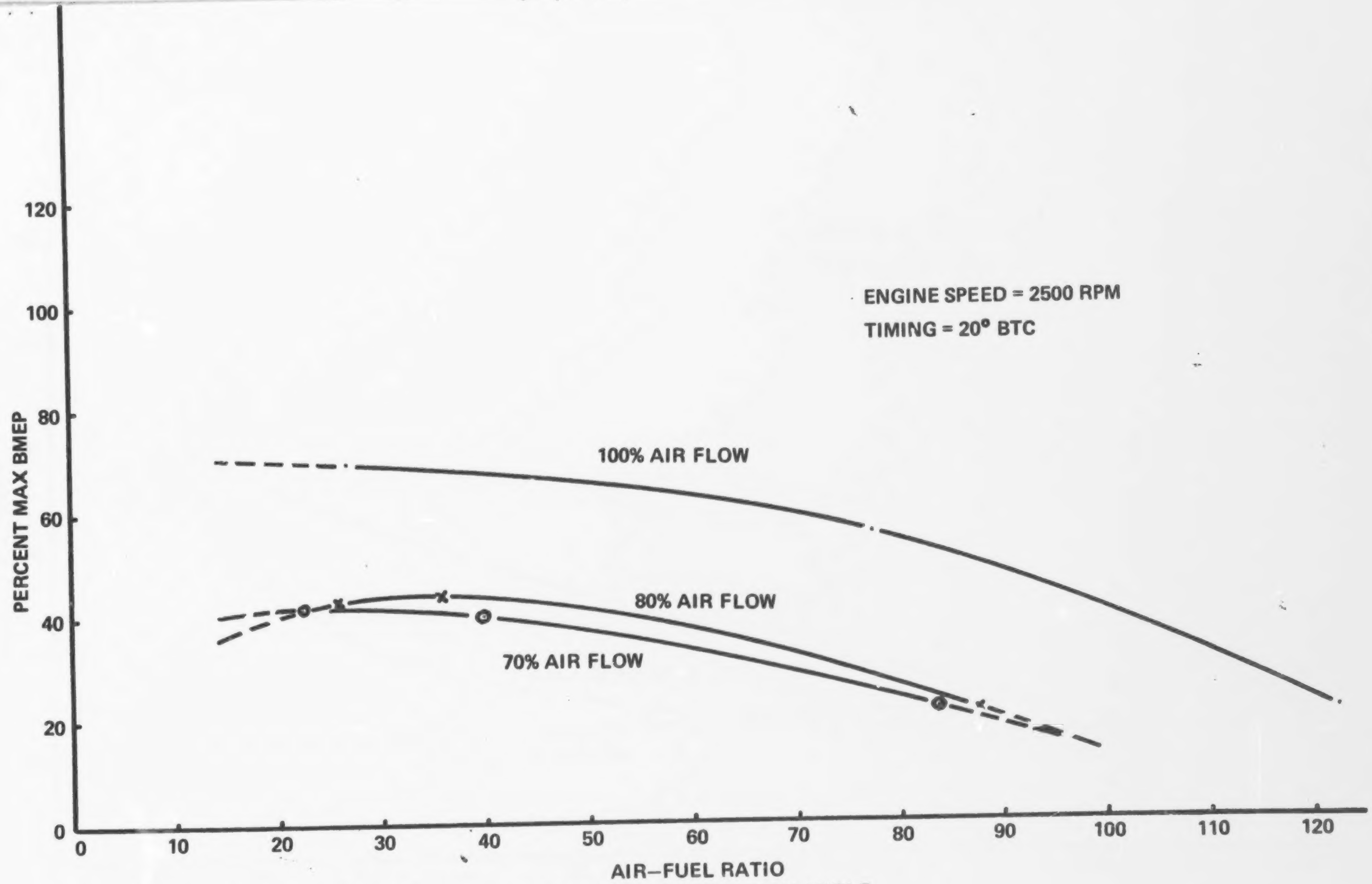


FIGURE 31B POWER–MIXTURE RELATIONSHIP – ADVANCED COMBINATION ANGLE

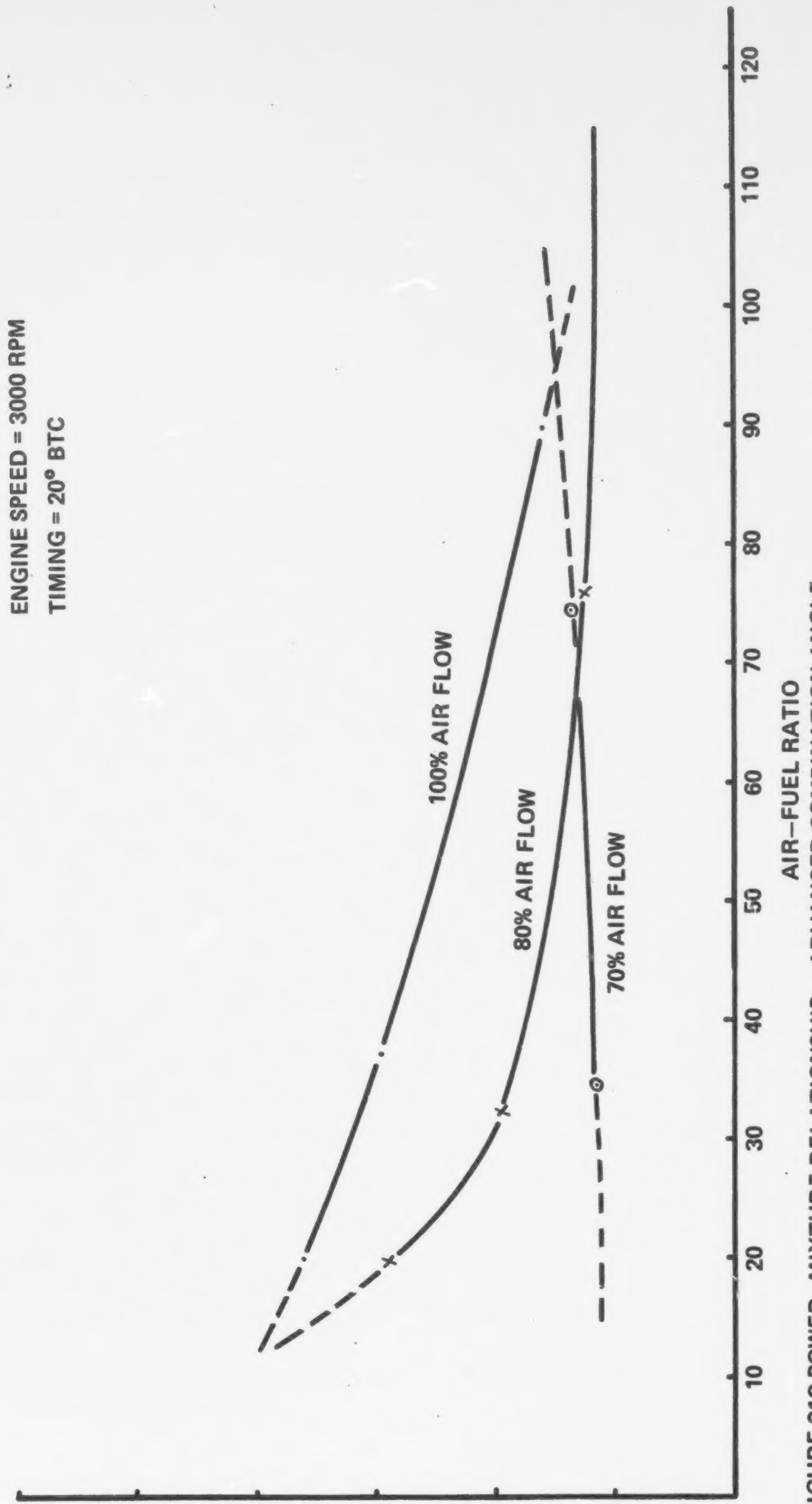


FIGURE 31C POWER–MIXTURE RELATIONSHIP – ADVANCED COMBINATION ANGLE

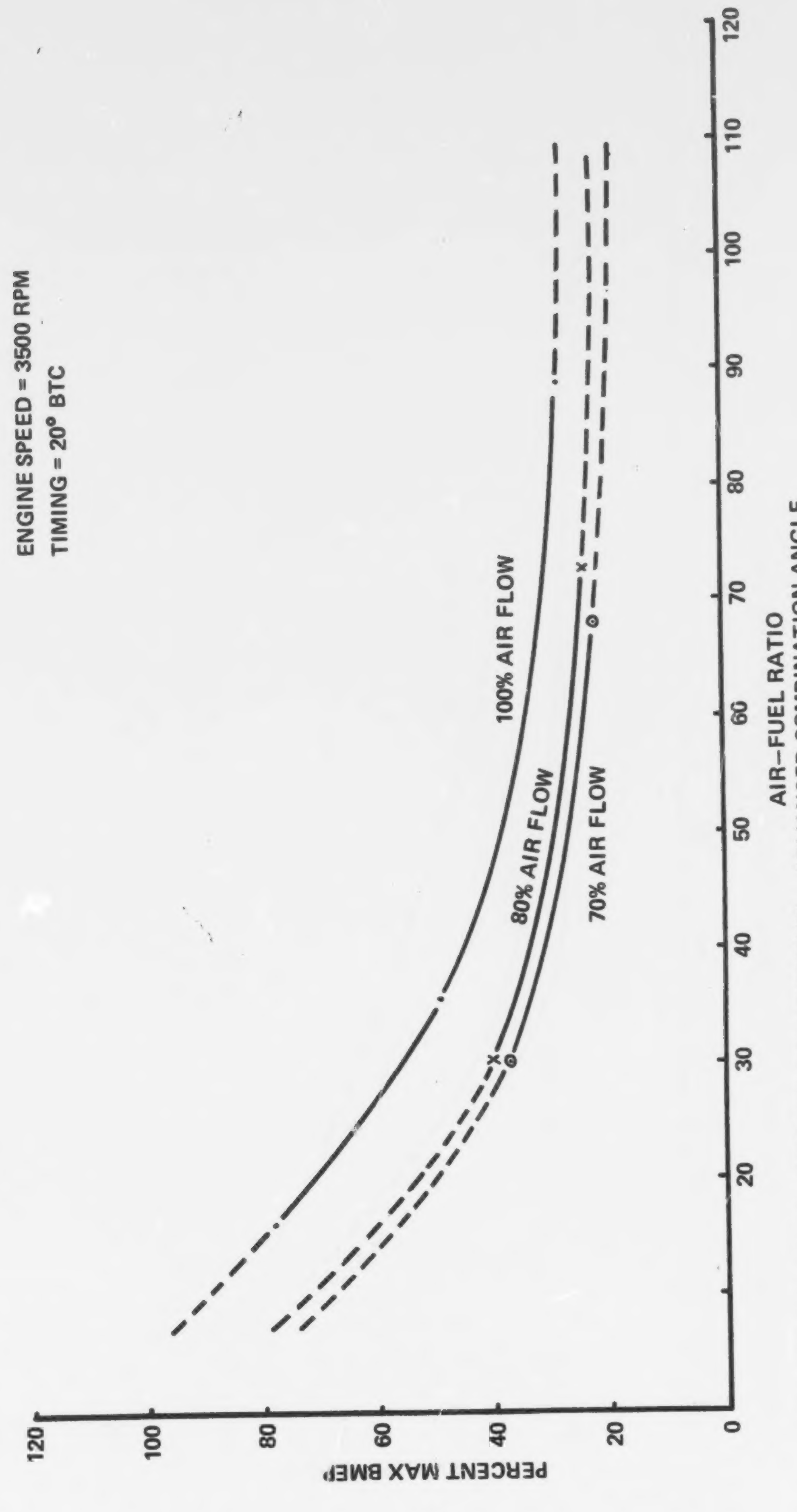
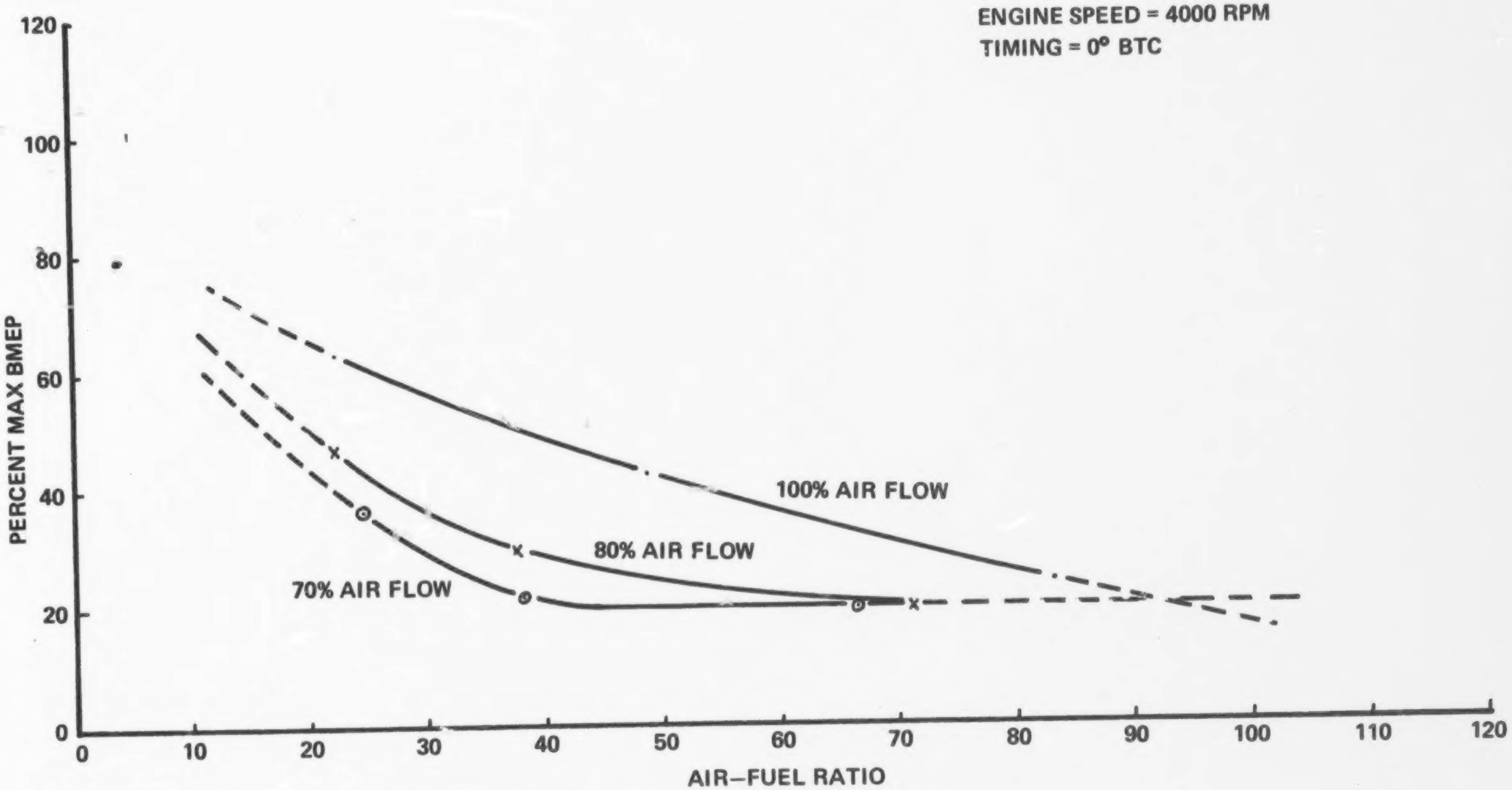


FIGURE 31D POWER–MIXTURE RELATIONSHIP – ADVANCED COMBINATION ANGLE



ENGINE SPEED = 4000 RPM
TIMING = 0° BTC

FIGURE 31E POWER–MIXTURE RELATIONSHIP – ADVANCED COMBINATION ANGLE

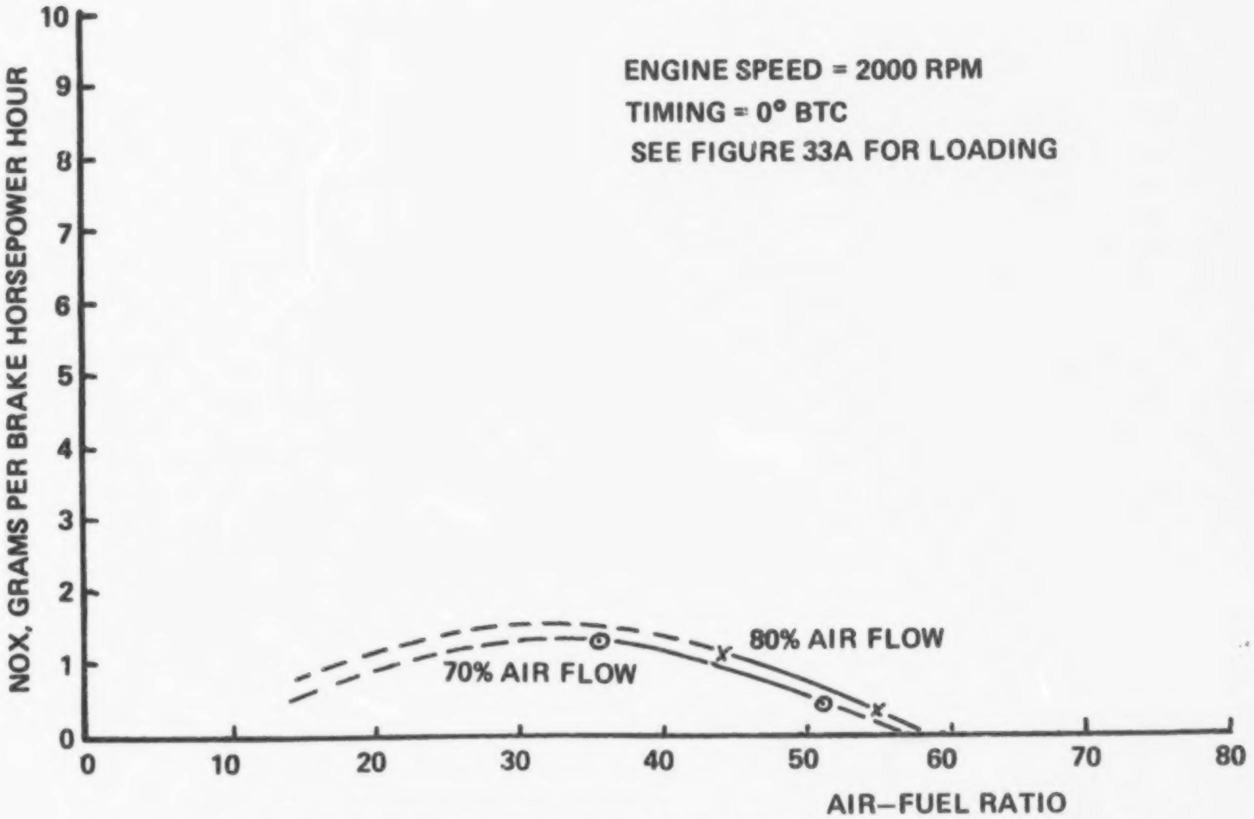


FIGURE 32A EMISSION-MIXTURE RELATIONSHIP - RETARDED COMBINATION ANGLE

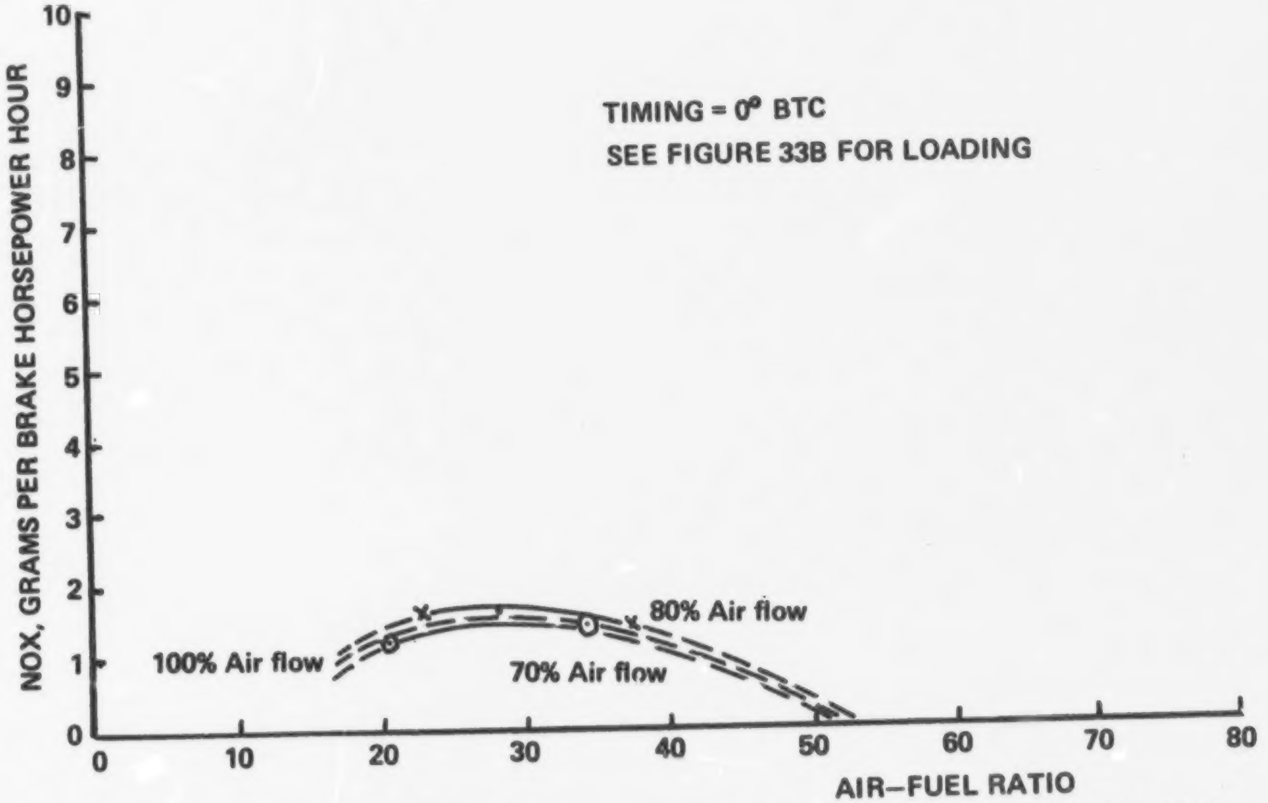


FIGURE 32B EMISSION–MIXTURE RELATIONSHIP – RETARDED COMBINATION ANGLE

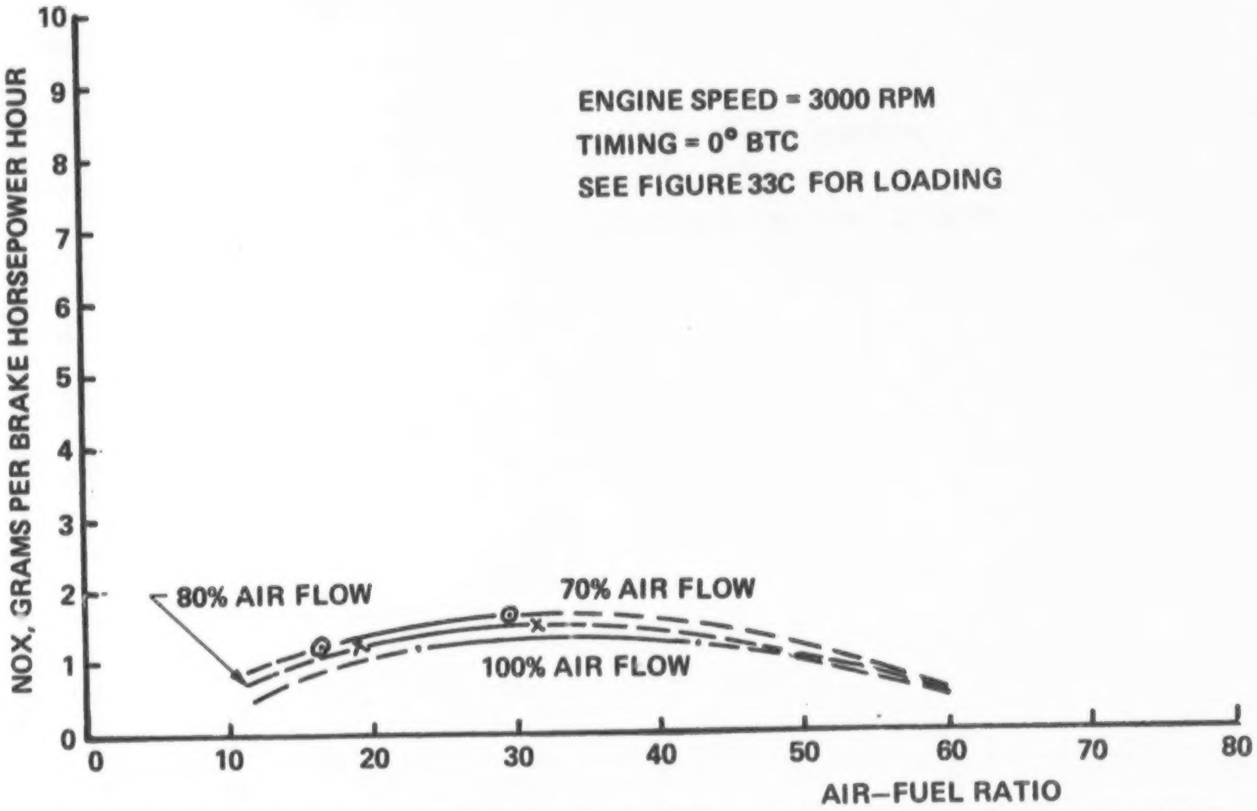


FIGURE 32C EMISSION–MIXTURE RELATIONSHIP – RETARDED COMBINATION ANGLE

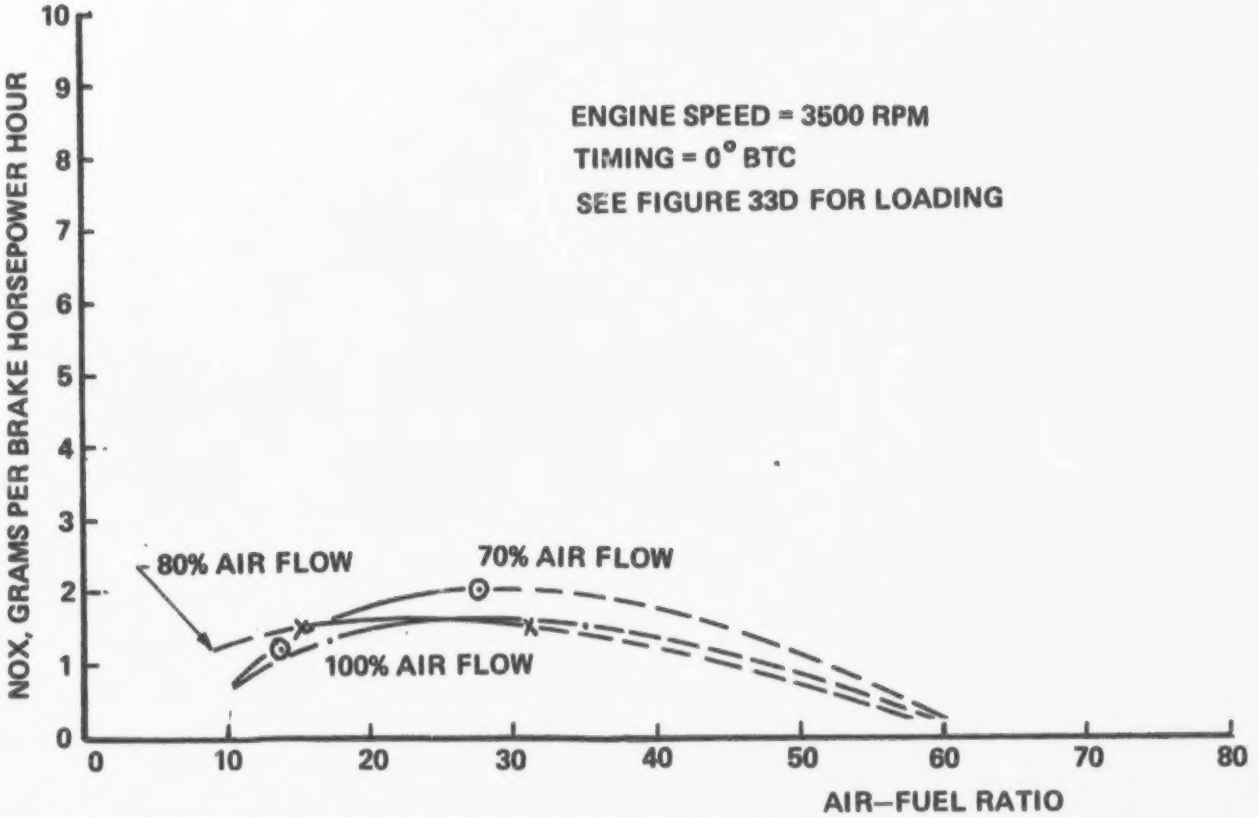


FIGURE 32D EMISSION–MIXTURE RELATIONSHIP – RETARDED COMBINATION ANGLE

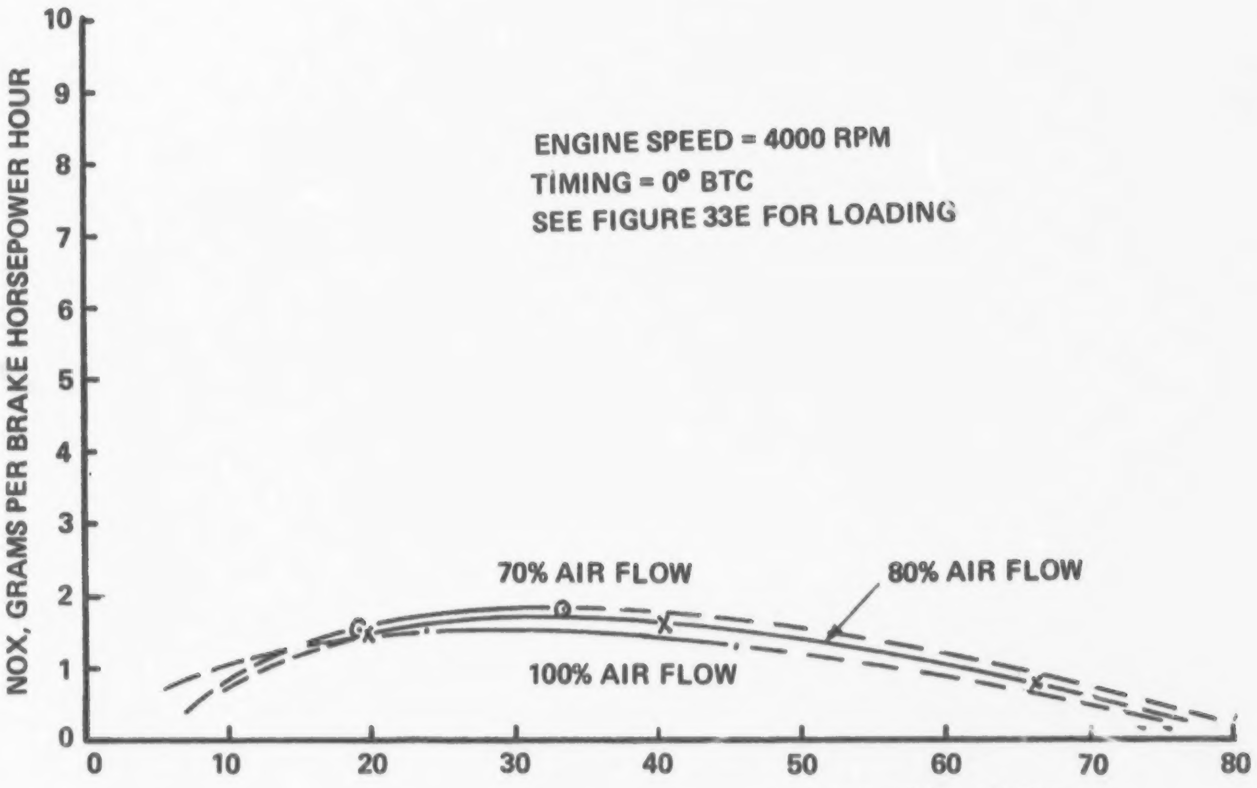


FIGURE 32E EMISSION–MIXTURE RELATIONSHIP – RETARDED COMBINATION ANGLE

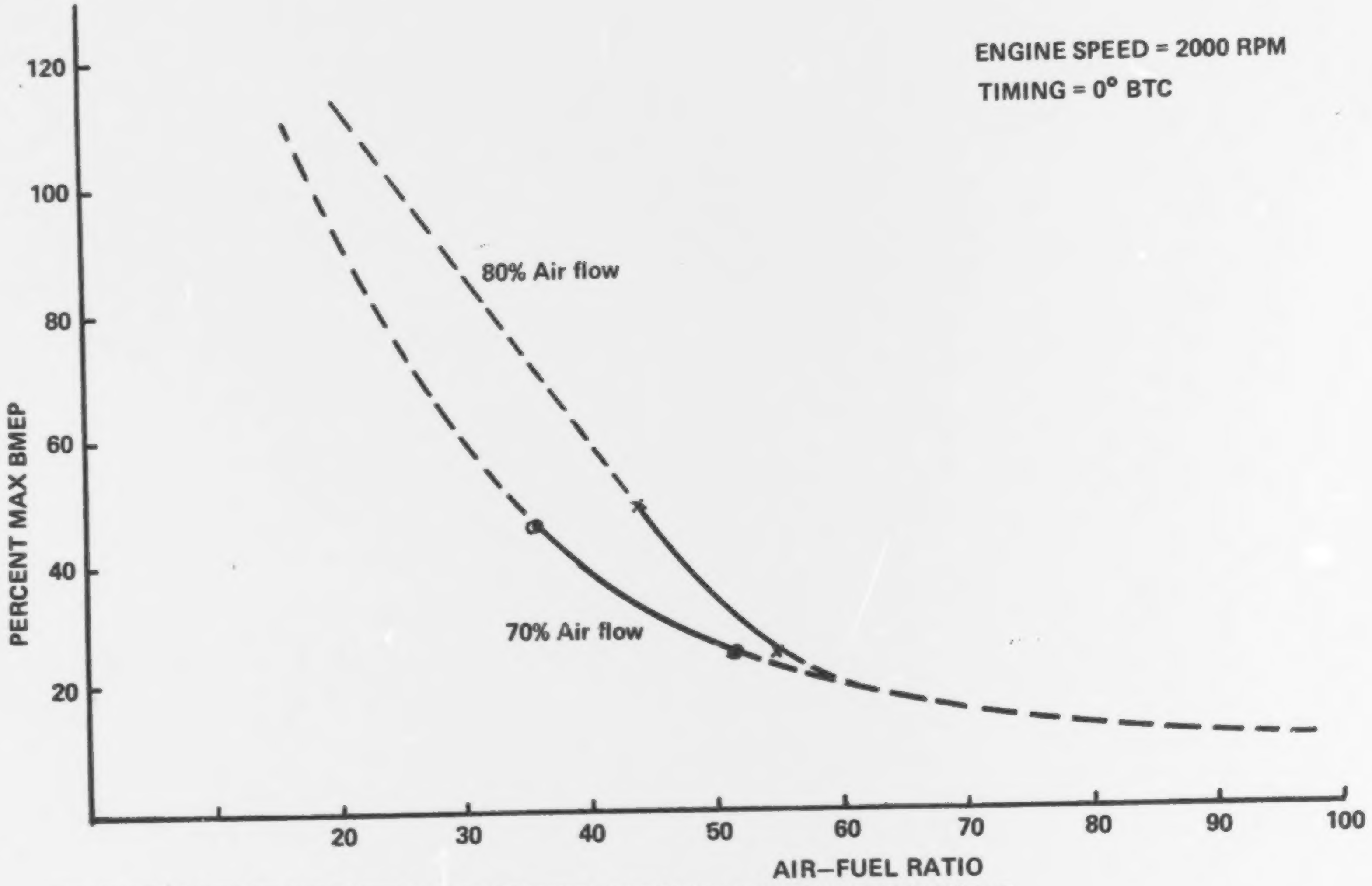


FIGURE 33A POWER-MIXTURE RELATIONSHIP - RETARDED COMBINATION ANGLE

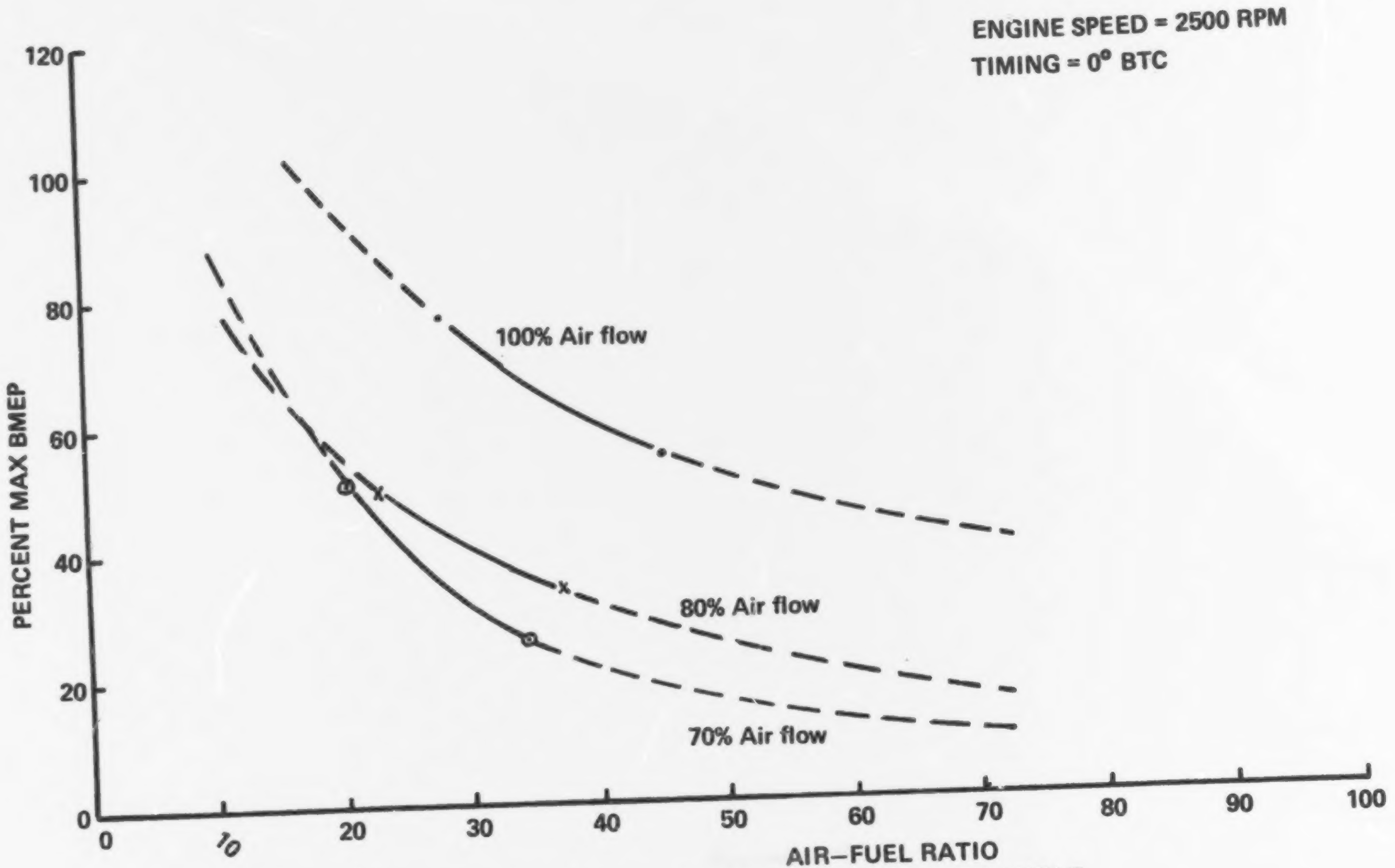


FIGURE 33B POWER-MIXTURE RELATIONSHIP - RETARDED COMBINATION ANGLE

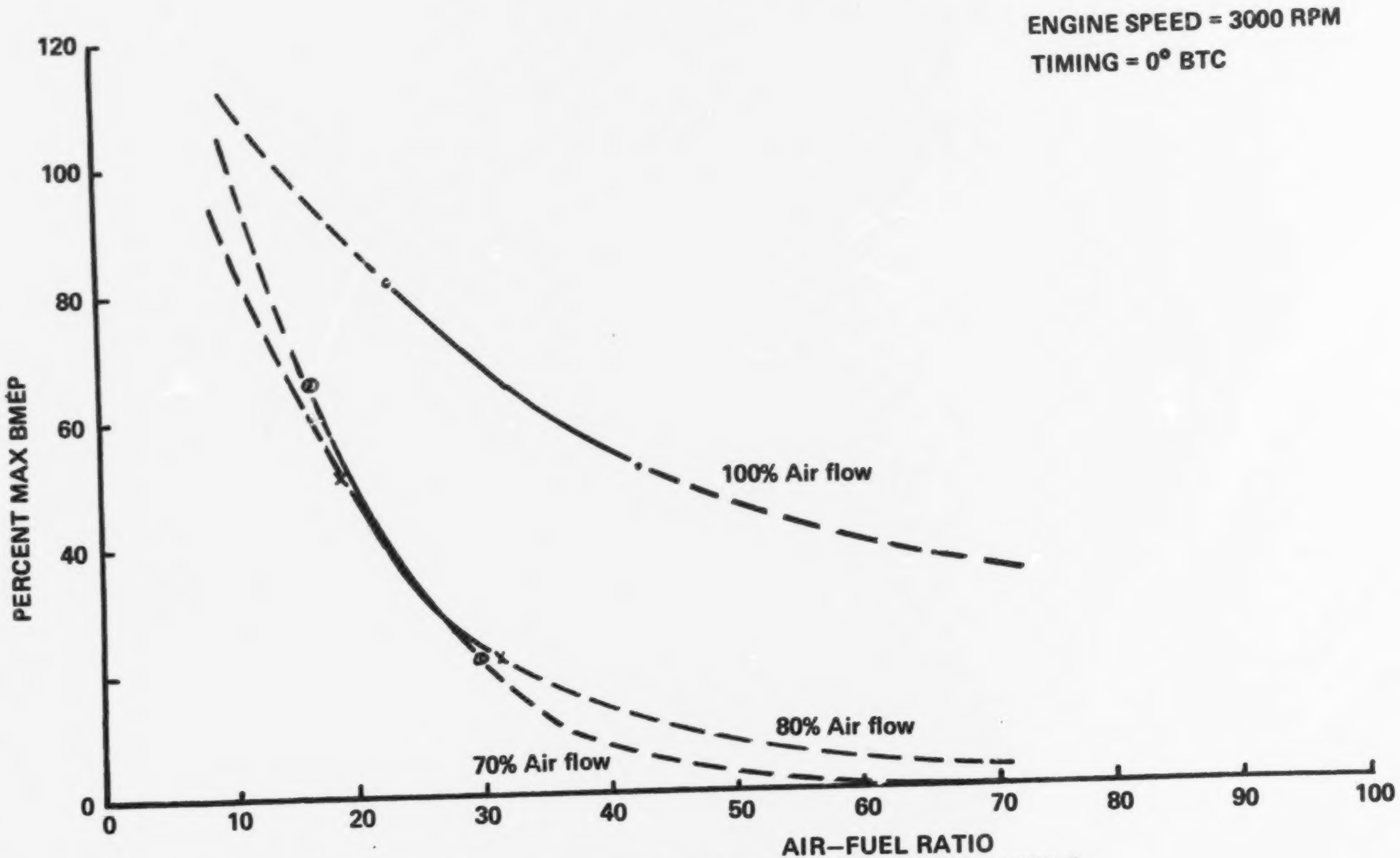


FIGURE 33C POWER-MIXTURE RELATIONSHIP - RETARDED COMBINATION ANGLE

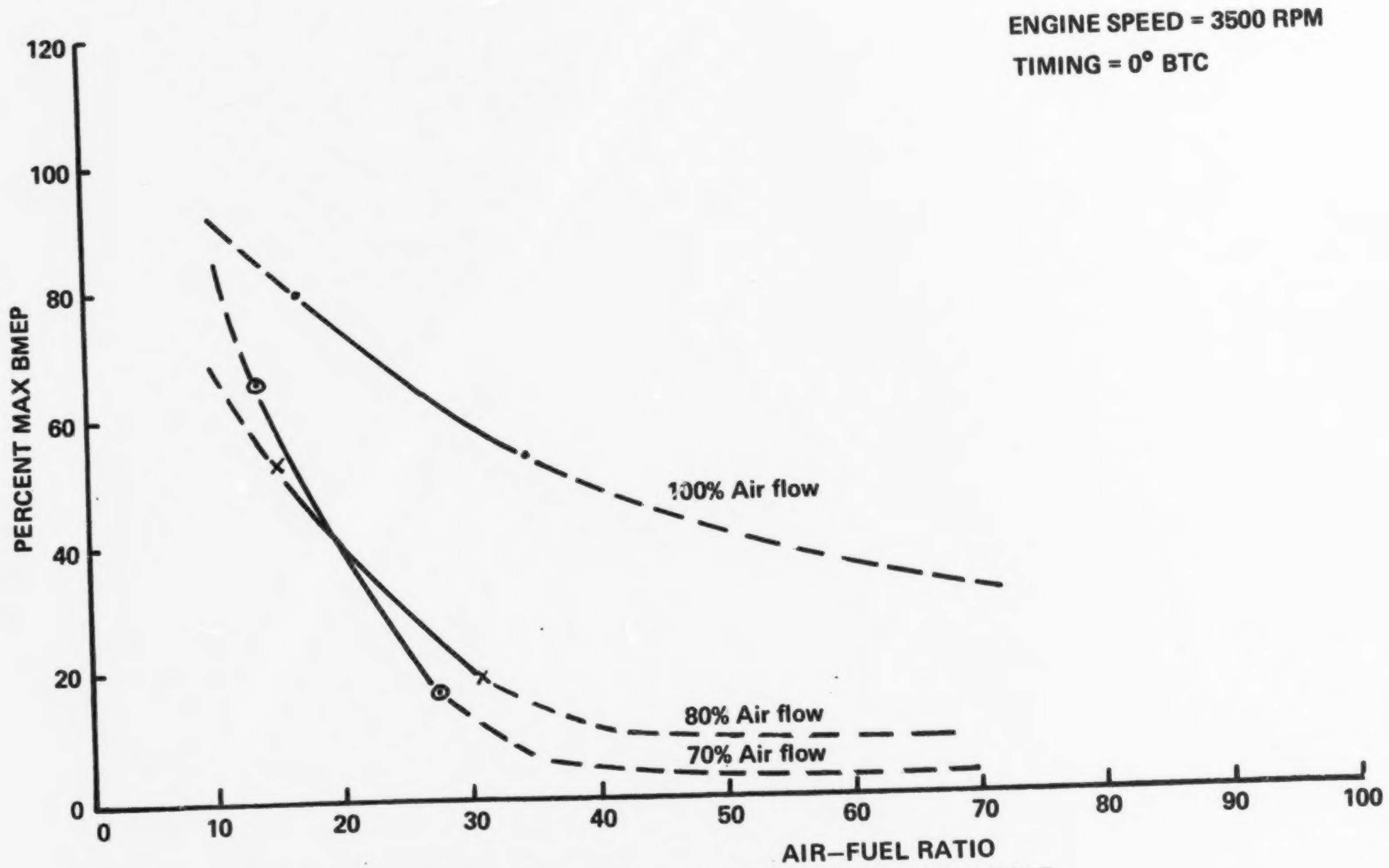


FIGURE 33D POWER-MIXTURE RELATIONSHIP - RETARDED COMBINATION ANGLE

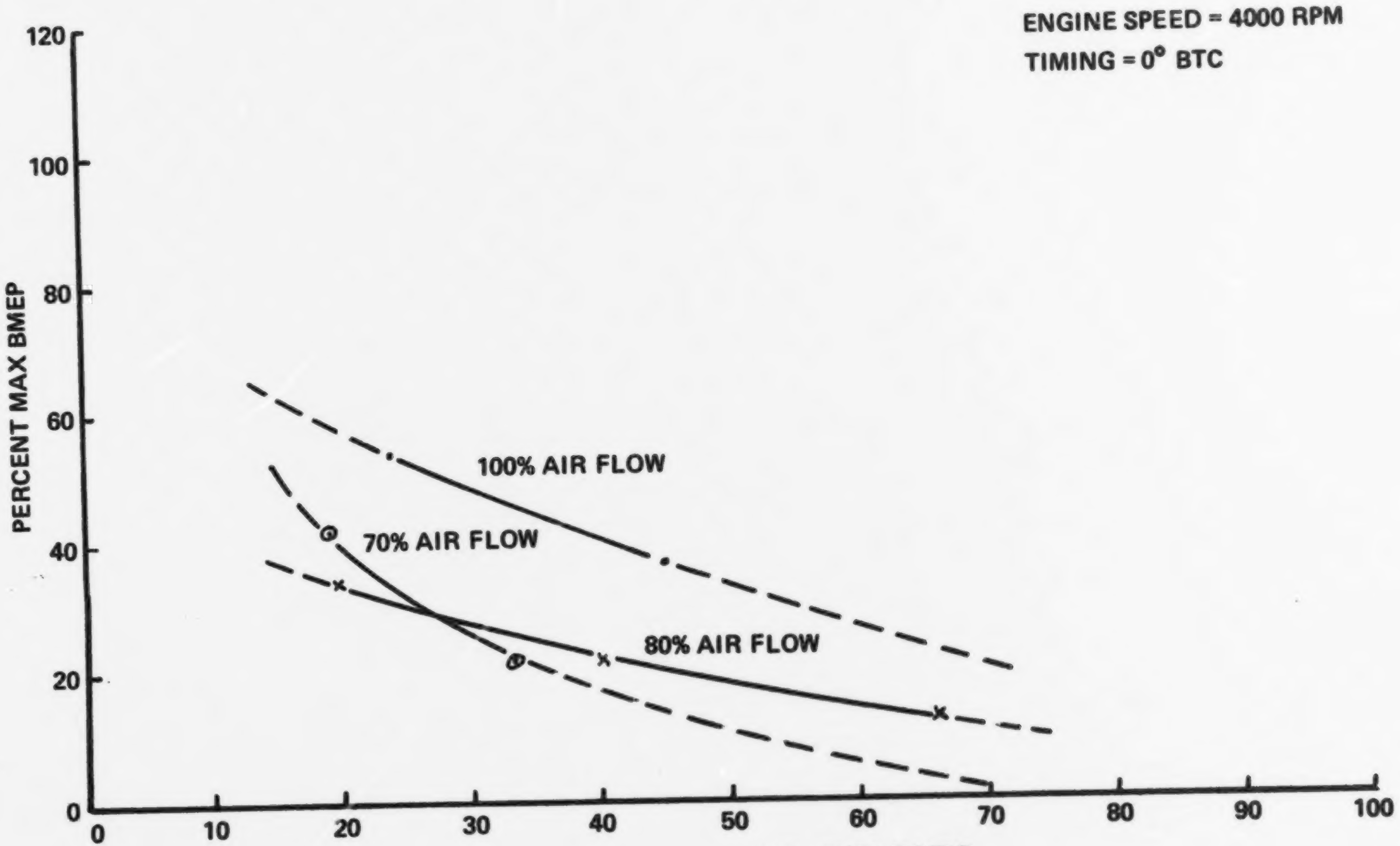


FIGURE 33E POWER-MIXTURE RELATIONSHIP - RETARDED COMBINATION ANGLE

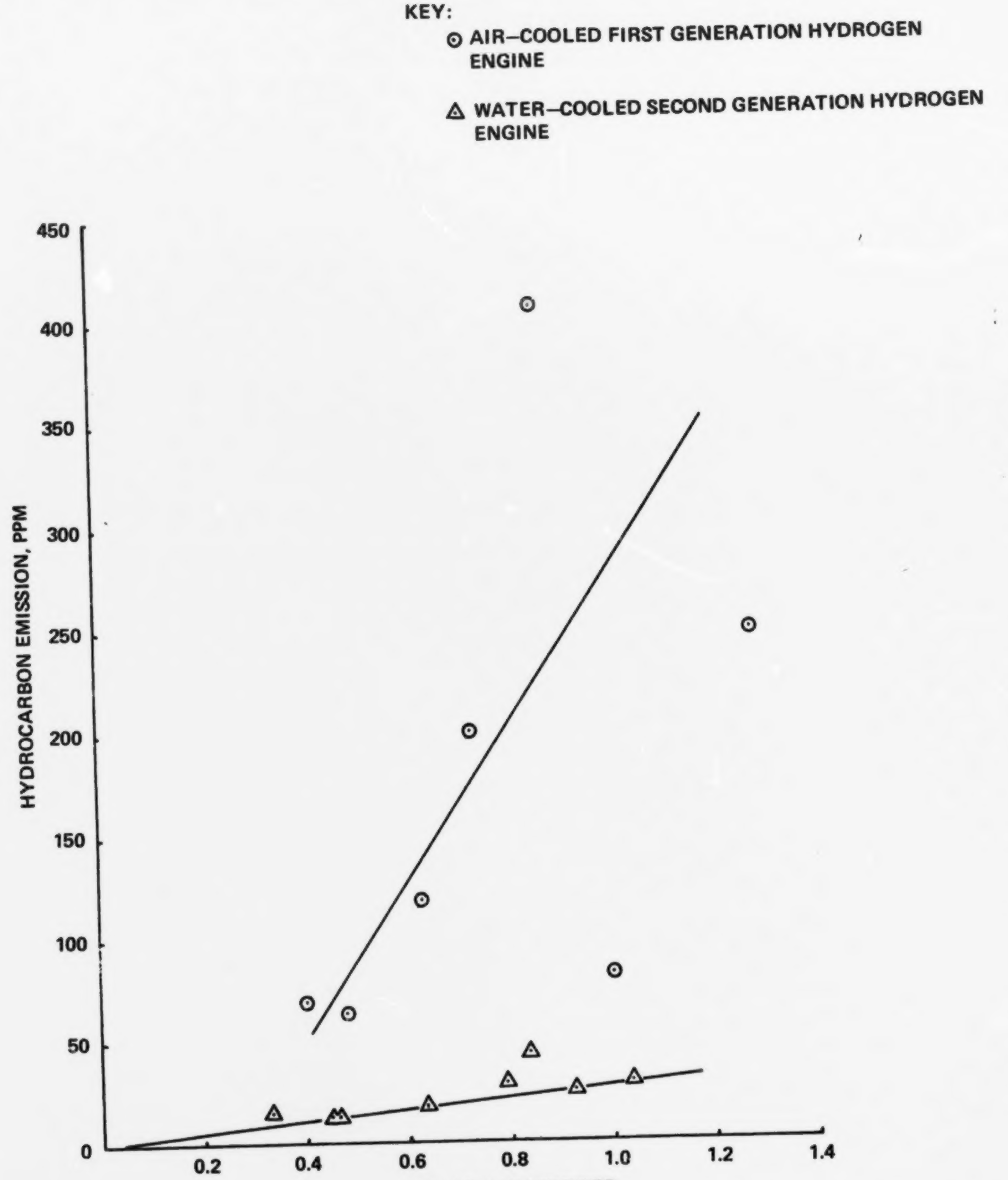


FIGURE 34 – ENGINE EMISSIONS (FROM TABLES 5 & 7)

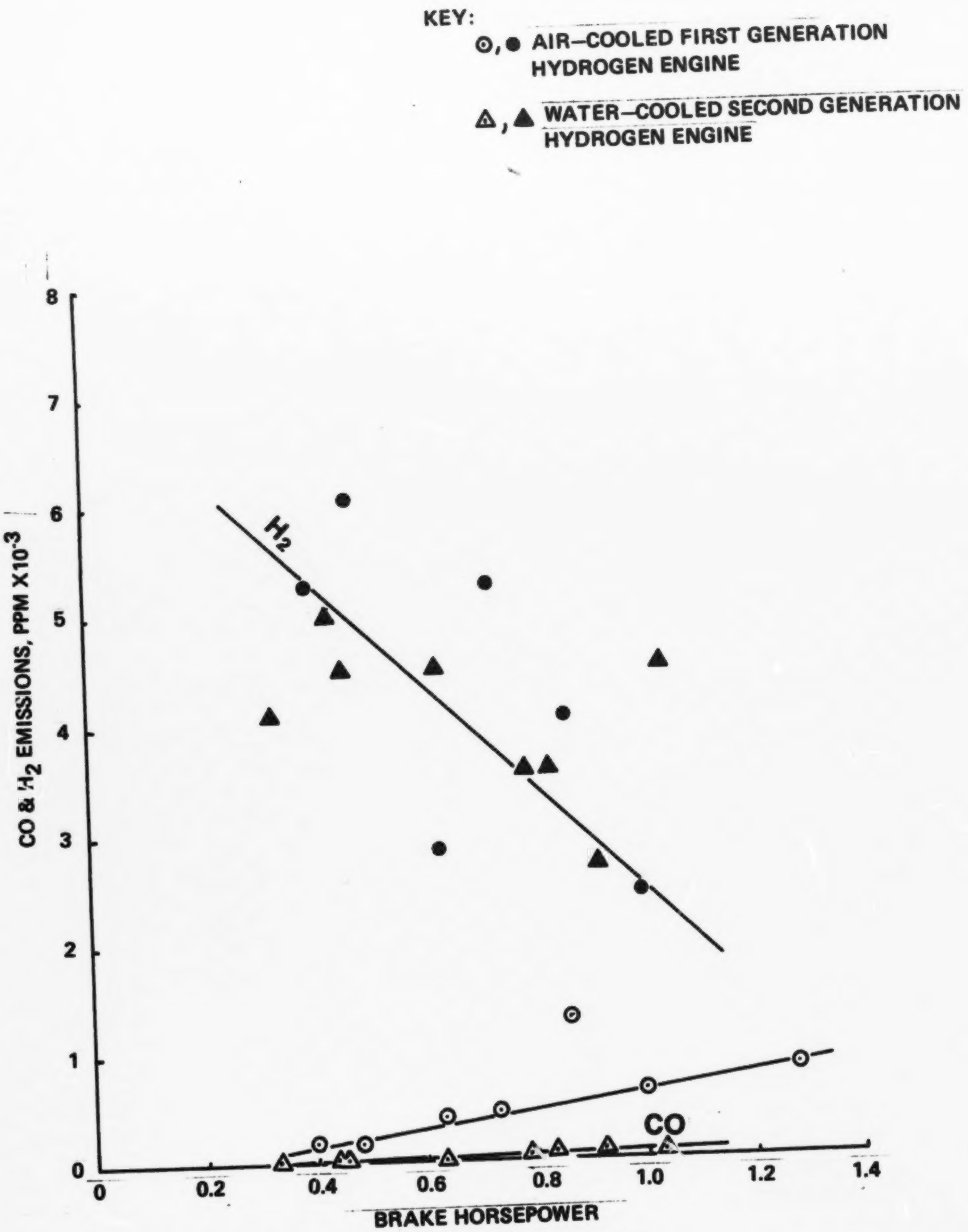
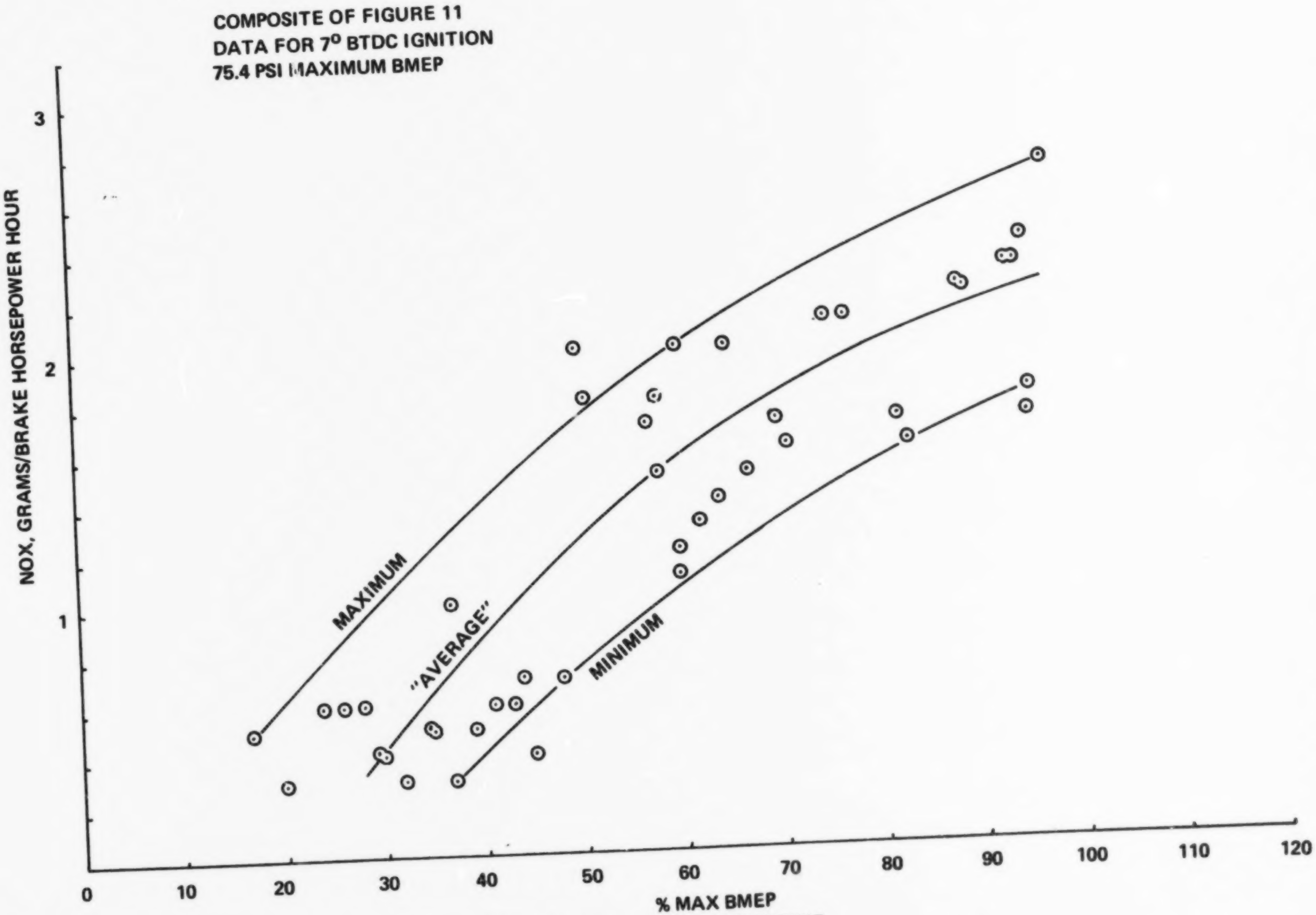


FIGURE 35 – ENGINE EMISSIONS (FROM TABLES 5 & 7)



COMPOSITE OF FIGURE 11
DATA FOR 7° BTDC IGNITION
75.4 PSI MAXIMUM BMEP

FIGURE 36 - ENGINE EMISSIONS VERSUS PERFORMANCE, AIR-COOLED ENGINE

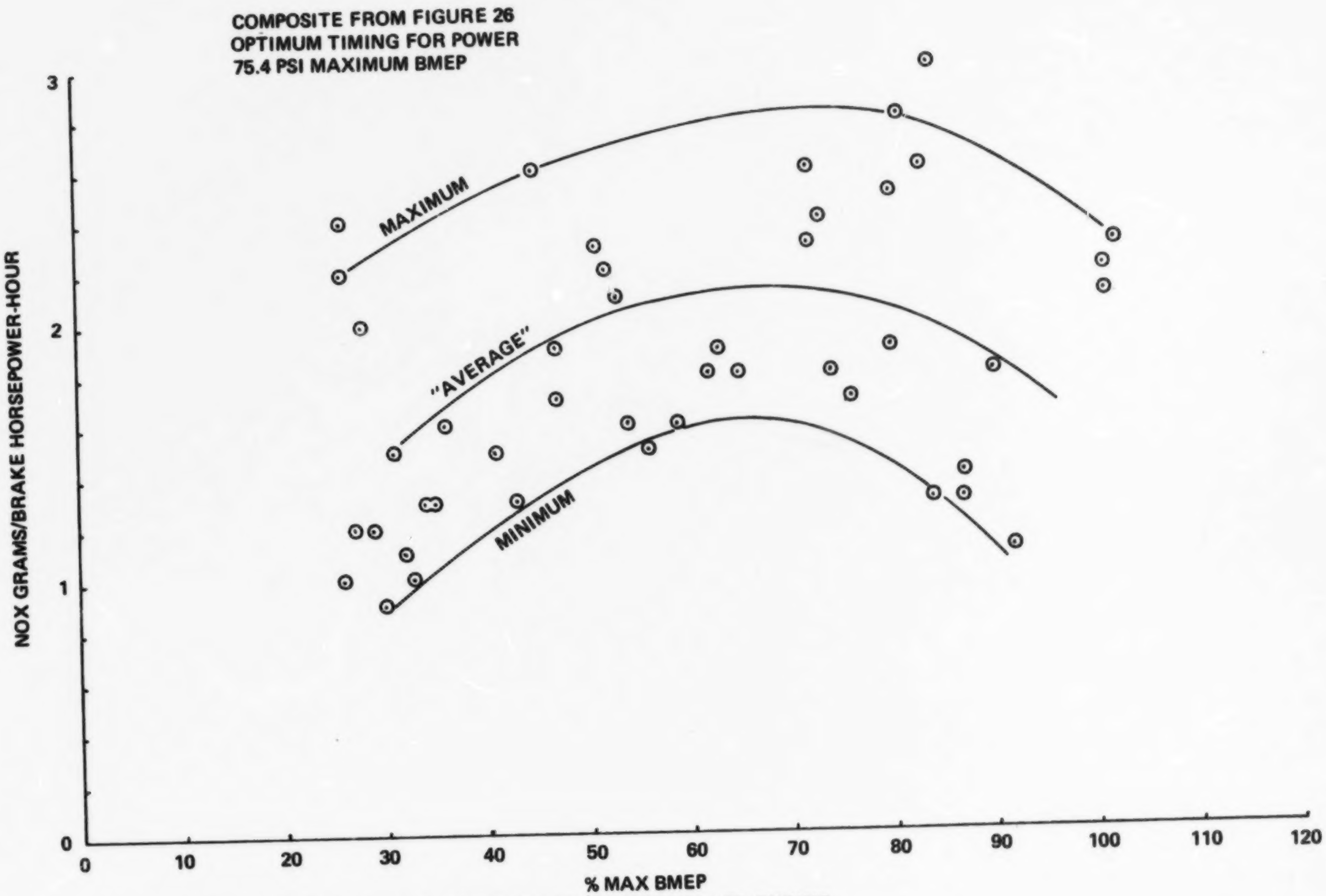

COMPOSITE FROM FIGURE 26
OPTIMUM TIMING FOR POWER
75.4 PSI MAXIMUM BMEP

FIGURE 37 ENGINE EMISSIONS VERSUS PERFORMANCE, WATER-COOLED ENGINE

TABLE 1 - Engine Specifications

Manufacturer	Clinton Engine Corporation
Type	Single cylinder, L-head, 4 cycle, air cooled
Model	494-0301
Bore	2.375"
Stroke	1.875"
Compression Ratio	6.5 to 1
Piston Displacement	8.3 cubic inches

TABLE 2 ENGINE OPERATIONAL DATA-FIRST SEQUENCE

THIS IS A HYDROGEN FUELED RUN

RUN NO	RPM	HP	TORQUE FT-PD	A/F	NOX PPM	% THR	EFBT %	IGN ANG	MA-PR IN-HG	BSFC PPHH	BMEP PSI	AFLO PPH	FFLC PPH	EX-T D-F	CHT D-F	CRT D-F	% STOK	%MAX PWR	%MAX BMEP	INJ-FROM BTDC	-ATDC	MBT DEG	GM PER	NOX BHPH	INJCT PRES
554	4000	1.62	2.12	45.2	212	85.	10.	7.	0.35	0.48	39.	34.8	0.77	1250	0	0	132.	65.	51.	28	38	0.		1.8	500
555	3500	1.78	2.68	35.4	325	83.	11.	7.	0.27	0.46	49.	29.2	0.82	1330	0	0	103.	71.	65.	28	38	0.		2.0	500
556	3000	1.60	2.80	36.9	258	79.	12.	7.	0.17	0.41	51.	24.4	0.66	1400	0	0	108.	64.	67.	28	38	0.		1.5	440
557	2500	1.23	2.57	43.5	201	82.	13.	7.	0.17	0.39	47.	21.0	0.48	1210	0	0	127.	49.	62.	28	38	0.		1.3	360
558	2000	0.70	1.84	69.9	63	86.	14.	7.	0.13	0.36	33.	17.7	0.25	860	0	0	204.	28.	44.	28	38	0.		0.7	230
559	3500	2.68	4.02	16.6	440	77.	8.	7.	0.22	0.62	73.	27.6	1.66	1420	0	0	48.	107.	97.	28	38	0.		2.7	920
560	3000	2.26	3.96	17.8	433	74.	9.	7.	0.15	0.57	72.	22.9	1.28	1340	0	0	52.	91.	95.	28	38	0.		2.4	780
561	4000	1.58	2.08	44.6	125	81.	11.	7.	0.33	0.47	38.	33.1	0.74	1350	0	0	130.	63.	50.	28	38	0.		1.0	480
563	2500	0.59	1.23	107.3	23	88.	14.	7.	0.18	0.36	22.	22.5	0.21	830	0	0	314.	23.	30.	28	38	0.		0.4	220
564	3000	0.87	1.52	85.0	21	88.	14.	7.	0.19	0.37	28.	27.0	0.32	970	0	0	248.	35.	37.	28	38	0.		0.3	270
565	3500	0.97	1.46	82.6	35	87.	13.	7.	0.26	0.39	27.	31.1	0.30	1020	0	0	241.	39.	35.	28	38	0.		0.5	310
566	4000	0.89	1.17	77.2	36	84.	10.	7.	0.37	0.50	21.	34.3	0.44	1050	0	0	226.	36.	28.	28	38	0.		0.6	340
567	2000	0.27	0.72	107.7	19	81.	9.	7.	0.64	0.57	13.	16.6	0.15	720	0	0	315.	11.	17.	28	38	0.		0.5	170
568	2500	0.39	0.83	99.9	13	79.	10.	7.	0.78	0.51	15.	20.1	0.20	820	0	0	292.	16.	20.	28	38	0.		0.3	195
569	3000	0.70	1.23	77.5	30	78.	11.	7.	0.69	0.44	22.	23.9	0.31	1020	0	0	226.	28.	30.	28	38	0.		0.4	260
570	3500	0.71	1.06	72.6	37	77.	9.	7.	0.76	0.53	19.	27.4	0.38	1070	0	0	212.	28.	26.	28	38	0.		0.6	290
571	4000	0.76	1.00	59.6	40	63.	9.	7.	0.77	0.56	18.	25.5	0.43	1130	0	0	174.	31.	24.	28	38	0.		0.6	360
572	2000	0.58	1.52	71.4	82	78.	13.	7.	0.55	0.39	28.	15.9	0.22	1000	0	0	209.	23.	37.	28	38	0.		1.0	200
573	2500	1.13	2.37	39.1	266	72.	12.	7.	0.73	0.42	43.	18.5	0.47	1390	0	0	114.	45.	57.	28	38	0.		1.7	260
574	3000	1.37	2.40	33.6	315	65.	11.	7.	0.64	0.45	44.	20.8	0.62	1510	0	0	98.	55.	58.	28	38	0.		1.8	410
575	3500	1.66	2.49	31.4	330	72.	10.	7.	0.68	0.49	45.	25.5	0.81	1600	0	0	92.	66.	60.	28	38	0.		2.0	500
576	4000	1.59	2.09	42.1	252	78.	10.	7.	0.44	0.48	38.	32.0	0.76	1590	0	0	123.	64.	50.	28	38	0.		2.0	500
577	2500	1.76	3.69	26.6	412	83.	11.	7.	0.15	0.46	67.	21.7	0.81	1430	0	0	78.	70.	89.	28	38	0.		2.2	480
578	4000	2.42	3.18	22.8	330	78.	8.	7.	0.33	0.59	58.	32.3	1.42	1650	0	0	67.	97.	77.	28	38	0.		2.1	850
579	2000	1.13	2.96	47.4	242	87.	15.	7.	0.10	0.34	54.	18.2	0.38	1215	0	0	139.	45.	71.	28	38	0.		1.6	310
580	4000	2.38	3.12	22.2	348	71.	9.	7.	0.76	0.56	57.	29.6	1.33	1520	0	0	65.	95.	75.	28	38	0.		2.1	860
581	3500	2.61	3.91	15.1	365	71.	8.	7.	0.58	0.66	71.	25.9	1.72	1200	0	0	44.	104.	94.	28	38	0.		2.3	1010
582	3000	2.20	3.86	19.8	425	74.	9.	7.	0.41	0.53	70.	23.0	1.16	1360	0	0	58.	88.	93.	28	38	0.		2.3	730
583	2500	1.76	3.69	22.2	407	76.	10.	7.	0.53	0.51	67.	19.8	0.89	1310	0	0	65.	70.	89.	28	38	0.		2.2	540
584	2000	1.10	2.90	42.3	282	81.	14.	7.	0.23	0.36	53.	17.0	0.40	1320	0	0	124.	44.	70.	28	38	0.		1.7	320
585	3000	0.43	0.76	90.0	10	63.	10.	7.	1.00	0.51	14.	20.0	0.22	935	0	0	263.	17.	18.	28	38	0.		0.2	220
586	2000	0.61	1.60	82.3	50	70.	17.	7.	0.78	0.29	29.	14.7	0.18	1040	0	0	241.	24.	39.	28	38	0.		0.5	225
587	2500	0.63	1.32	96.3	25	71.	16.	7.	0.78	0.31	24.	18.8	0.19	1030	0	0	282.	25.	32.	28	38	0.		0.3	240
588	3000	0.98	1.71	70.2	68	70.	15.	7.	0.76	0.32	31.	22.1	0.32	1050	0	0	205.	39.	41.	28	38	0.		0.6	315
589	3500	1.18	1.77	67.3	63	69.	16.	7.	0.53	0.32	32.	25.4	0.38	1230	0	0	197.	47.	43.	28	38	0.		0.6	350
590	4000	1.09	1.43	66.0	41	68.	13.	7.	0.62	0.40	26.	28.7	0.43	1190	0	0	193.	44.	35.	28	38	0.		0.5	400
591	2000	0.72	1.88	46.9	63	61.	13.	7.	0.75	0.38	34.	12.7	0.27	1130	0	0	137.	29.	45.	28	38	0.		0.4	250
592	2500	1.19	2.50	38.8	212	66.	13.	7.	0.57	0.37	45.	17.3	0.44	1400	0	0	114.	48.	60.	28	38	0.		1.2	360
593	3000	1.52	2.67	30.3	266	63.	11.	7.	0.59	0.43	48.	20.0	0.66	1520	0	0	88.	61.	64.	28	38	0.		1.4	450
594	3500	1.59	2.39	27.5	247	62.	10.	7.	0.75	0.52	43.	22.6	0.82	1560	0	0	80.	64.	58.	28	38	0.		1.5	520

TABLE 2 ENGINE OPERATIONAL DATA-FIRST SEQUENCE (CONT.)

THIS IS A HYDROGEN FUELED RUN

RUN NO	RPM	HP	TORQUE FT-PD	A/F	NOX PPM	% THR	EFBT %	IGN ANG	MA-PR IN-HG	BSFC PPHH	BMEP PSI	AFLO PPH	FFLO PPH	EX-T D-F	CHT D-F	CRT D-F	% STOK	%MAX PWR	%MAX BMEP	INJ-FROM BTDC-ATDC		MBT DEG	GM PER	NOX BHPH	INJCT PRES
595	4000	1.52	1.99	42.0	93	71.	11.	7.	0.41	0.46	36.	29.6	0.70	1320	0	0	123.	61.	48.	28	38	0.		0.7	480
596	2000	0.95	2.50	38.4	188	68.	13.	7.	0.48	0.39	45.	14.2	0.37	1190	0	0	112.	38.	60.	28	38	0.		1.1	300
597	2500	1.64	3.45	23.6	326	68.	11.	7.	0.50	0.46	63.	17.9	0.76	1380	0	0	69.	66.	83.	28	38	0.		1.6	480
598	3000	2.26	3.96	16.6	353	63.	9.	7.	0.46	0.53	72.	20.0	1.20	1160	0	0	49.	9C.	95.	28	38	0.		1.8	840
599	3500	2.64	3.96	14.3	303	63.	8.	7.	0.59	0.62	72.	23.3	1.63	1240	0	0	42.	106.	95.	28	38	0.		1.7	980
600	4000	2.59	3.40	18.1	293	64.	9.	7.	0.57	0.57	62.	26.9	1.49	1490	0	0	53.	104.	82.	28	38	0.		1.7	890
601	2500	1.09	2.29	45.3	93	78.	12.	0.	0.13	0.41	42.	20.2	0.44	1330	0	0	133.	44.	55.	14	60	0.		0.7	360
602	3000	1.24	2.18	42.7	146	86.	10.	0.	0.19	0.50	40.	26.6	0.62	1430	0	0	125.	50.	52.	14	60	0.		1.2	440
603	3500	1.49	2.23	34.6	198	84.	8.	0.	0.27	0.59	41.	30.6	0.88	1520	0	0	101.	60.	54.	14	60	0.		1.5	540
604	4000	1.19	1.56	45.2	111	85.	8.	0.	0.35	0.65	28.	35.0	0.78	1500	0	0	132.	47.	37.	14	60	0.		1.3	490
605	2500	1.52	3.20	28.1	259	87.	10.	0.	0.15	0.52	58.	22.4	0.80	1460	0	0	82.	61.	77.	14	60	0.		1.6	480
606	3000	1.96	3.42	23.2	193	86.	8.	0.	0.19	0.59	62.	26.6	1.15	1560	0	0	68.	78.	82.	14	60	0.		1.2	740
607	3500	2.21	3.31	16.9	170	79.	7.	0.	0.24	0.76	60.	28.4	1.68	1440	0	0	49.	88.	80.	14	60	0.		1.3	1000
608	4000	1.70	2.23	23.8	160	82.	6.	0.	0.33	0.83	41.	33.7	1.42	1760	0	0	69.	68.	54.	14	60	0.		1.5	910
609	4000	0.40	0.53	66.1	25	68.	4.	0.	1.00	1.11	10.	29.4	0.44	1210	0	0	193.	16.	13.	14	60	0.		0.8	320
610	2000	0.39	1.02	54.9	21	68.	7.	0.	0.82	0.69	19.	14.8	0.27	1150	0	0	160.	16.	25.	14	60	0.		0.3	200
611	2500	0.67	1.41	37.2	141	67.	7.	0.	0.82	0.73	26.	18.2	0.49	1420	0	0	109.	27.	34.	14	60	0.		1.4	320
612	3000	0.52	0.91	31.4	94	64.	4.	0.	0.81	1.27	17.	2C.8	0.66	1550	0	0	92.	21.	22.	14	60	0.		1.5	400
613	3500	0.54	0.80	30.7	81	66.	3.	0.	0.75	1.52	15.	24.9	0.81	1600	0	0	90.	21.	19.	14	60	0.		1.5	460
614	4000	0.70	0.91	40.2	93	72.	4.	0.	0.82	1.11	17.	31.2	0.78	1500	0	0	118.	28.	22.	14	60	0.		1.6	480
615	2000	0.77	2.02	44.0	124	78.	10.	0.	0.51	0.49	37.	16.7	0.38	1270	0	0	129.	31.	49.	14	60	0.		1.1	280
616	2500	0.99	2.08	22.9	171	71.	6.	0.	0.72	0.85	38.	19.2	0.84	1480	0	0	67.	40.	50.	14	60	0.		1.6	480
617	3000	1.22	2.13	19.0	125	71.	5.	0.	0.27	0.99	39.	22.9	1.20	1460	0	0	56.	49.	51.	14	60	0.		1.3	760
618	3500	1.46	2.19	15.0	138	68.	4.	0.	0.59	1.17	40.	25.5	1.7C	1400	0	0	44.	58.	53.	14	60	0.		1.5	1010
619	4000	1.08	1.41	19.8	109	65.	4.	0.	0.81	1.32	26.	28.2	1.42	1620	0	0	58.	43.	34.	14	60	0.		1.5	890
620	2000	0.39	1.02	51.4	28	63.	7.	0.	0.89	0.67	19.	13.5	0.26	1170	0	0	150.	16.	25.	14	60	0.		0.4	200
621	2500	0.51	1.08	34.4	119	61.	5.	0.	0.94	0.93	20.	16.4	0.48	1410	0	0	101.	21.	26.	14	60	0.		1.4	320
622	3000	0.52	0.91	29.9	101	62.	4.	0.	0.86	1.28	17.	19.9	0.67	1590	0	0	87.	21.	22.	14	60	0.		1.6	400
623	3500	0.46	0.69	27.4	95	61.	3.	0.	0.89	1.82	13.	23.1	0.84	1690	0	0	80.	18.	17.	14	60	0.		2.0	480
624	4000	0.70	0.91	33.4	115	66.	4.	0.	0.98	1.22	17.	28.5	0.85	1530	0	0	98.	28.	22.	14	60	0.		1.8	500
625	2000	0.73	1.91	35.7	169	67.	9.	0.	0.76	0.56	35.	14.5	0.41	1320	0	0	105.	29.	46.	14	60	0.		1.3	300
626	2500	1.02	2.13	20.5	137	64.	6.	0.	0.77	0.83	39.	17.3	0.85	1460	0	0	60.	41.	51.	14	60	0.		1.2	480
627	3000	1.57	2.74	16.8	157	64.	6.	0.	0.72	0.79	50.	20.8	1.24	1290	0	0	49.	63.	66.	14	60	0.		1.2	780
628	3500	1.83	2.74	13.5	145	61.	5.	0.	0.96	0.93	50.	22.9	1.70	1200	0	0	39.	73.	66.	14	60	0.		1.2	1010
629	4000	1.33	1.74	19.2	133	64.	5.	0.	0.85	1.07	32.	27.4	1.43	1580	0	0	56.	53.	42.	14	60	0.		1.5	900
630	2500	0.41	0.87	122.4	9	98.	10.	20.	0.18	0.51	16.	25.7	0.21	680	0	0	358.	17.	21.	44	19	0.		0.2	220
631	3000	0.75	1.32	89.6	6	94.	11.	20.	0.23	0.44	24.	29.6	0.33	880	0	0	262.	30.	32.	44	19	0.		0.1	280
632	3500	0.77	1.15	88.9	13	92.	10.	20.	0.30	0.49	21.	33.5	0.38	940	0	0	260.	31.	28.	44	19	0.		0.2	305
633	4000	0.75	0.98	83.1	28	89.	8.	20.	0.40	0.59	18.	37.0	0.44	950	0	0	243.	30.	24.	44	19	0.		0.6	340
634	2000	0.61	1.60	76.3	149	95.	12.	20.	0.12	0.43	29.	19.8	0.26	880	0	0	223.	24.	39.	44	19	0.		2.1	255

TABLE 2 ENGINE OPERATIONAL DATA-FIRST SEQUENCE (CONT.)

THIS IS A HYDROGEN FUELED RUN

RUN NO	RPM	HP	TORQUE FT-PD	A/F	NOX PPM	% THR	EFBT %	IGN ANG	MA-PR IN-HG	BSFC PPHH	BMEP PSI	AFLO PPH	FFLO PPH	EX-T D-F	CHT D-F	CRT D-F	% STOK	%MAX PWR	%MAX BMEP	INJ-FROM BTDC	ATDC	MBT DEG	GM PER	NOX BHPH	INJCT PRES
635	2500	1.11	2.33	77.5	360	132.	12.	20.	0.14	0.40	42.	34.5	0.44	1200	0	0	227.	44.	56.	44	19	0.		4.8	340
636	3000	1.40	2.44	37.5	472	84.	10.	20.	0.21	0.50	44.	26.4	0.70	1350	0	0	110.	56.	59.	44	19	0.		3.4	420
637	3500	1.37	2.05	35.6	460	83.	8.	20.	0.26	0.62	37.	30.3	0.85	1500	0	0	104.	55.	49.	44	19	0.		3.8	480
638	4000	1.35	1.77	48.8	125	87.	9.	20.	0.39	0.55	32.	36.2	0.74	1200	0	0	143.	54.	43.	44	19	0.		1.3	440
639	2000	0.91	2.39	48.3	462	89.	12.	20.	0.10	0.42	43.	18.7	0.39	1110	0	0	141.	36.	58.	44	19	0.		3.8	315
640	2500	1.38	2.89	26.8	610	83.	8.	20.	0.13	0.59	53.	21.8	0.81	1380	0	0	78.	55.	70.	44	19	0.		4.1	455
641	3000	1.72	3.00	20.0	492	78.	7.	20.	0.17	0.71	55.	24.4	1.22	1300	0	0	59.	69.	72.	44	19	0.		3.6	660
642	3500	2.15	3.23	16.3	410	75.	6.	20.	0.23	0.79	59.	27.6	1.69	1240	0	0	48.	86.	78.	44	19	0.		3.1	910
643	4000	1.99	2.61	22.4	462	79.	7.	20.	0.31	0.74	47.	33.0	1.47	1580	0	0	65.	80.	63.	44	19	0.		3.7	800
644	2000	0.25	0.65	115.9	60	86.	8.	20.	0.54	0.63	12.	17.9	0.15	730	0	0	339.	10.	16.	44	19	0.		1.9	200
645	2500	0.41	0.87	87.6	48	74.	9.	20.	0.77	0.54	16.	19.5	0.22	870	0	0	256.	17.	21.	44	19	0.		1.0	220
646	3000	0.59	1.04	75.8	56	74.	10.	20.	0.80	0.52	19.	23.2	0.31	1010	0	0	222.	24.	25.	44	19	0.		0.9	255
647	3500	0.66	0.98	72.7	81	74.	9.	20.	0.89	0.57	18.	27.2	0.37	1050	0	0	213.	26.	24.	44	19	0.		1.4	300
648	4000	0.62	0.81	71.1	89	73.	7.	20.	0.96	0.69	15.	30.5	0.43	1080	0	0	208.	25.	20.	44	19	0.		1.8	340
649	2000	0.46	1.21	62.1	174	71.	10.	20.	0.77	0.52	22.	15.0	0.24	930	0	0	182.	18.	29.	44	19	0.		2.3	225
650	2500	0.87	1.83	35.8	420	67.	9.	20.	0.89	0.56	33.	17.5	0.49	1260	0	0	105.	35.	44.	44	19	0.		3.2	240
651	3000	0.91	1.60	32.4	336	67.	7.	20.	0.81	0.71	29.	21.1	0.65	1500	0	0	95.	37.	39.	44	19	0.		3.0	400
652	3500	1.10	1.66	30.4	370	69.	7.	20.	0.91	0.75	30.	25.1	0.82	1500	0	0	89.	44.	40.	44	19	0.		3.3	480
653	4000	0.96	1.26	37.7	267	73.	6.	20.	0.78	0.84	23.	30.7	0.81	1600	0	0	110.	39.	30.	44	19	0.		3.2	500
654	2000	0.77	2.02	43.0	399	81.	10.	20.	0.62	0.49	37.	16.2	0.38	1180	0	0	126.	31.	49.	44	19	0.		3.3	300
655	2500	1.07	2.25	25.9	543	84.	7.	20.	0.54	0.76	41.	21.0	0.81	1400	0	0	76.	43.	54.	44	19	0.		4.7	460
656	3000	1.39	2.42	19.9	455	80.	6.	20.	0.36	0.87	44.	23.9	1.20	1290	0	0	58.	55.	58.	44	19	C.		4.1	650
657	4000	1.49	1.96	22.4	442	75.	6.	20.	0.59	0.89	36.	29.9	1.33	1600	0	0	66.	60.	47.	44	19	0.		4.2	720
658	2000	0.28	0.73	102.3	136	82.	9.	20.	0.55	0.58	13.	16.4	0.16	880	0	0	299.	11.	18.	44	19	0.		3.5	200
659	2500	0.43	0.91	83.8	85	75.	10.	20.	0.87	0.52	16.	18.6	0.22	1010	0	0	245.	17.	22.	44	19	0.		1.6	210
660	3000	0.65	1.14	74.4	106	78.	10.	20.	0.73	0.48	21.	23.5	0.32	1140	0	0	218.	26.	27.	44	19	C.		1.6	260
661	3500	0.60	0.90	68.1	115	73.	8.	20.	0.91	0.63	16.	25.7	0.38	1190	0	0	199.	24.	22.	44	19	0.		2.1	300
662	4000	0.65	0.85	66.5	119	74.	7.	20.	0.94	0.69	15.	29.6	0.44	1230	0	0	195.	26.	20.	44	19	0.		2.3	330
663	2000	0.57	1.49	49.3	376	68.	10.	20.	0.80	0.49	27.	13.7	0.28	1180	0	0	144.	23.	36.	44	19	0.		3.6	240
664	2500	0.79	1.66	39.9	524	71.	9.	20.	0.81	0.56	30.	17.8	0.44	1350	0	0	117.	32.	40.	44	19	0.		4.5	320
665	3000	0.55	0.96	34.6	392	70.	5.	20.	0.77	1.10	18.	21.0	0.61	1600	0	0	101.	22.	23.	44	19	0.		5.6	380
666	3500	1.03	1.55	30.2	432	67.	7.	20.	0.98	0.76	28.	23.6	0.78	1400	0	0	88.	41.	37.	44	19	0.		3.9	440
667	4000	0.69	0.91	38.2	320	75.	4.	20.	0.76	1.13	16.	29.8	0.78	1630	0	0	112.	28.	22.	44	19	0.		5.3	480
668	2000	0.77	2.02	39.6	555	79.	10.	20.	0.57	0.52	37.	15.9	0.40	1200	0	0	116.	31.	49.	44	19	0.		4.4	310
669	2500	0.82	1.72	22.5	462	72.	5.	20.	0.45	0.98	31.	18.1	0.80	1320	0	0	66.	33.	42.	44	19	0.		4.9	460
670	4000	1.18	1.55	24.5	432	87.	4.	20.	0.75	1.20	28.	34.9	1.42	1400	0	0	72.	47.	37.	44	19	0.		5.8	760

TABLE 3 ENGINE TEST FORM

CAST-IRON ENGINE ANALYSIS DATA SHEET

Test Date_______________

Remarks_______________

Fuel Type_______________

Wet Bulb Temperature_______________ °F

Test Observers_______________

	Raw Data	Final Data	Punch Card Data	
				(1-3)
Run No.				(4-5)
Dry Bulb Air Temperature			.	(6-9)
Barometric Pressure, Inches Hg.			.	(10-13)
Correction Factor, Humidity				(14-17)
Engine RPM			.	(18-19)
Dyn. Load, Pounds Force			.	(20-22)
Intake Air Meter, inches H_2O			.	(23-25)
Air Flow, Lb. per hr.				(26-29)
Exhaust Gas Temp., °F				(30-32)
Cylinder Head Temp., °F				(33-35)
Crankcase Temp., °F			.	(36-38)
Manifold Vacuum, Inches Oil			±	(39-41)
Ignition, Degrees from TDC			.	(42-45)
Test Time, Min.				(46-49)
Injector Delivery Press, Psig.			.	(50-52)
Hydrogen Flowmeter Reading				(53-55)
NOx Reading, ppm.			.	(56-58)
Gasoline Flow, gm.				(59-60)
Injection start, DEG, BTC				(61-62)
Injection End, DEG, ATC			±	(63-65)
Minimum Angle for Best Torque, DEG				

Note: decimal point is "understood," it does not appear on punch card.

TABLE 4 ENGINE OPERATIONAL DATA - LOW POWER EXPERIMENTS

THIS IS A HYDROGEN FUELED RUN

RUN NO	RPM	HP	TORQUE FT-PD	A/F	NOX PPM	% THR	EFBT %	IGN ANG	MA-PR IN-HG	BSFC PPHH	BMEP PSI	AFLO PPH	FFLO PPH	EX-T D-F	CHT D-F	CRT D-F	% STOK	%MAX PWR	%MAX BMEP	INJ-FROM BTDC-ATDC		MBT DEG	GM PER	NOX BHPH	INJCT PRES
671	2500	0.57	1.19	122.2	22	103.	13.	7.	0.17	0.37	22.	25.7	0.21	700	0	0	357.	23.	29.	28	38	0.		0.4	230
672	2500	0.51	1.08	92.0	26	80.	12.	7.	0.78	0.42	20.	19.9	0.22	840	0	0	269.	21.	26.	28	38	0.		0.4	230
673	2500	0.49	1.02	85.7	28	75.	11.	7.	0.91	0.45	19.	18.8	0.22	900	0	0	251.	19.	25.	28	38	0.		0.5	230
674	2500	0.43	0.90	68.4	38	63.	9.	7.	1.09	0.54	16.	15.8	0.23	1010	0	0	200.	17.	22.	28	38	0.		0.6	220
675	2500	0.51	1.08	107.1	26	93.	12.	7.	0.51	0.42	20.	23.2	0.22	780	0	0	313.	21.	26.	28	38	0.		0.5	230
676	2000	0.43	1.14	124.5	30	100.	13.	7.	0.12	0.37	21.	20.0	0.16	710	0	0	364.	17.	27.	28	38	0.		0.6	200
677	2000	0.41	1.08	107.4	34	91.	12.	7.	0.53	0.41	20.	18.3	0.17	740	0	0	314.	16.	26.	28	38	0.		0.7	200
678	2000	0.39	1.02	98.2	34	88.	11.	7.	0.63	0.46	19.	17.6	0.18	770	0	0	287.	16.	25.	28	38	0.		0.7	200
679	2000	0.39	1.02	86.9	34	79.	11.	7.	0.73	0.47	19.	15.8	0.18	810	0	0	254.	16.	25.	28	38	0.		0.6	200
680	2000	0.39	1.02	71.9	36	67.	10.	7.	0.86	0.48	19.	13.3	0.19	880	0	0	210.	16.	25.	28	38	0.		0.5	200
681	3000	0.78	1.37	92.1	17	96.	13.	7.	0.22	0.40	25.	28.7	0.31	950	0	0	269.	31.	33.	28	38	0.		0.3	310
682	2000	0.37	0.96	134.6	14	100.	12.	7.	0.12	0.40	18.	20.0	0.15	620	0	0	393.	15.	23.	28	38	0.		0.3	195
683	2500	0.51	1.08	116.4	17	98.	12.	7.	0.15	0.41	20.	24.5	0.21	720	0	0	340.	21.	26.	28	38	0.		0.4	230
684	3000	0.72	1.26	82.5	34	87.	11.	7.	0.55	0.44	23.	26.0	0.32	910	0	0	241.	29.	30.	28	38	0.		0.5	310
685	3000	0.68	1.20	79.1	38	82.	11.	7.	0.66	0.45	22.	24.5	0.31	930	0	0	231.	27.	29.	28	38	0.		0.6	300
686	3000	0.65	1.14	74.8	38	78.	10.	7.	0.73	0.48	21.	23.4	0.31	940	0	0	219.	26.	27.	28	38	0.		0.6	300
687	3000	0.45	0.79	67.5	48	70.	7.	7.	0.86	0.69	14.	21.1	0.31	1060	0	0	197.	18.	19.	28	38	0.		0.9	300
688	3500	0.84	1.26	86.3	39	94.	11.	7.	0.28	0.45	23.	32.8	0.38	960	0	0	252.	34.	30.	28	38	0.		0.7	350
689	3500	0.88	1.32	79.4	57	86.	12.	7.	0.67	0.43	24.	29.9	0.38	990	0	0	232.	35.	32.	28	38	0.		0.8	350
690	3500	0.84	1.26	75.9	63	82.	11.	7.	0.81	0.45	23.	28.6	0.38	1010	0	0	222.	34.	30.	28	38	0.		0.9	350
691	3500	0.80	1.20	69.2	77	75.	11.	7.	0.93	0.47	22.	26.1	0.38	1070	0	0	202.	32.	29.	28	38	0.		1.1	350
692	3500	0.76	1.14	64.2	83	69.	10.	7.	1.03	0.49	21.	24.0	0.37	1110	0	0	188.	30.	27.	28	38	0.		1.1	350
693	4000	0.63	0.83	86.8	12	94.	7.	7.	0.44	0.70	15.	38.6	0.44	860	0	0	254.	25.	20.	28	38	0.		0.3	350
694	4000	0.46	0.60	82.5	32	81.	6.	7.	0.95	0.88	11.	33.1	0.40	840	0	0	241.	18.	14.	28	38	0.		1.0	340
695	4000	0.46	0.60	74.7	37	73.	6.	7.	1.12	0.88	11.	30.0	0.40	910	0	0	218.	18.	14.	28	38	0.		1.0	340
696	4000	0.41	0.54	71.5	42	70.	5.	7.	1.17	0.97	10.	28.7	0.40	930	0	0	209.	17.	13.	28	38	0.		1.2	340
697	4000	0.37	0.49	66.3	49	64.	5.	7.	1.27	1.07	9.	26.3	0.40	990	0	0	194.	15.	12.	28	38	0.		1.5	340
698	3500	0.86	1.29	90.4	24	95.	11.	7.	0.32	0.44	23.	34.1	0.38	820	0	0	264.	34.	31.	28	38	0.		0.4	320
699	3000	0.73	1.29	97.1	23	97.	12.	7.	0.24	0.42	23.	30.0	0.31	720	0	0	284.	29.	31.	28	38	0.		0.4	280
700	2500	0.48	1.00	113.2	25	98.	11.	7.	0.19	0.47	18.	25.2	0.22	640	0	0	331.	19.	24.	28	38	0.		0.6	220
701	2000	0.40	1.06	125.3	29	102.	12.	7.	0.14	0.41	19.	20.9	0.17	590	0	0	366.	16.	25.	28	38	0.		0.7	190
702	3000	1.00	1.74	46.1	130	91.	8.	7.	0.21	0.61	32.	28.0	0.61	1330	0	0	135.	40.	42.	28	38	0.		1.4	450
703	3500	1.28	1.91	36.6	130	90.	7.	7.	0.30	0.69	35.	32.2	0.88	1450	0	0	107.	51.	46.	28	38	0.		1.2	580

TABLE 5

Comprehensive Exhaust Gas Analysis

Air-Cooled Engine

Run and Sample No.	H_2 (1)	O_2 (1)	N_2 (1)	CO (1)	CO_2 (1)	Hydrocarbon (2)
Blank	0.000	20.00	77.9	0.000	0.0	9
693	0.284	15.40	82.1	0.039	0.01	118
698	0.405	14.37	81.8	0.128	0.15	407
699	0.526	15.76	81.8	0.044	0.00	200
700	0.607	16.66	80.8	0.017	0.00	63
701	0.526	16.50	81.1	0.017	0.00	69
702	0.243	9.38	88.2	0.061	0.17	84
703	1.130	7.01	89.3	0.084	0.33	249

(1) Values given are in mol (or volume) percent

(2) Values given are in ppmc (parts per million on the basis of gram atoms carbon per mol of gas).

TABLE 6 ENGINE OPERATIONAL DATA-WATER JACKETED ENGINE

THIS IS A HYDROGEN FUELED RUN

RUN NO	RPM	HP	TORQUE FT-PD	A/F	NOX PPM	% THR	EFBT %	IGN ANG	MA-PR IN-HG	BSFC PPHH	BMEP PSI	AFLO PPH	FFLO PPH	EX-T D-F	CHT D-F	CRT D-F	% STOK	%MAX PWR	%MAX BMEP	INJ-FROM BTDC-	ATDC	MBT DEG	GM PER	NOX BHPH	INJCT PRES
704	2000	0.33	0.86	140.4	66	106.	11.	7.	0.13	0.45	16.	20.8	0.15	405	0	0	410.	13.	21.	35	25	0.		1.9	215
705	2500	0.46	0.97	124.6	35	105.	11.	7.	0.19	0.45	18.	25.8	0.21	500	0	0	364.	19.	23.	35	25	0.		0.9	220
706	3000	0.83	1.45	96.4	79	101.	13.	7.	0.23	0.37	26.	29.8	0.31	651	0	0	282.	33.	35.	35	25	0.		1.2	275
707	3500	0.92	1.39	93.4	87	103.	12.	7.	0.33	0.41	25.	35.2	0.38	730	0	0	273.	37.	33.	35	25	0.		1.4	325
708	4000	0.79	1.03	83.4	92	95.	9.	7.	0.40	0.57	19.	37.1	0.44	790	0	0	244.	31.	25.	35	25	0.		1.9	370
709	4000	1.55	2.04	45.9	283	93.	10.	7.	0.39	0.51	37.	36.5	0.80	1020	0	0	134.	62.	49.	35	25	0.		2.6	540
710	2000	0.44	1.15	141.9	92	107.	15.	-1.	0.13	0.34	21.	21.0	0.15	410	0	0	415.	18.	28.	35	25	0.		2.0	200
711	2500	0.63	1.33	118.4	65	103.	15.	-1.	0.18	0.34	24.	25.3	0.21	510	0	0	346.	25.	32.	35	25	0.		1.1	215
712	3000	1.03	1.80	91.5	107	101.	16.	-2.	0.23	0.32	33.	29.7	0.32	680	0	0	268.	41.	43.	35	25	0.		1.3	275
713	3500	1.12	1.68	89.6	115	97.	15.	2.	0.31	0.33	31.	33.2	0.37	715	0	0	262.	45.	41.	35	25	0.		1.5	320
714	4000	1.15	1.51	79.7	115	93.	13.	4.	0.37	0.40	27.	36.3	0.46	800	0	0	233.	46.	36.	35	25	0.		1.6	400
715	2000	0.80	2.10	78.8	220	96.	16.	15.	0.10	0.31	38.	19.5	0.25	725	0	0	230.	32.	51.	35	25	0.		2.3	260
716	2500	1.41	2.97	47.5	407	90.	15.	10.	0.15	0.34	54.	22.9	0.48	995	0	0	139.	57.	72.	35	25	0.		2.6	360
717	3000	1.73	3.03	42.3	395	88.	14.	5.	0.22	0.37	55.	26.8	0.63	1080	0	0	124.	69.	73.	35	25	0.		2.4	415
718	3500	1.98	2.97	39.9	372	88.	13.	1.	0.30	0.39	54.	31.1	0.78	1130	0	0	117.	79.	72.	35	25	0.		2.3	460
719	4000	1.69	2.22	48.3	258	85.	12.	3.	0.37	0.42	40.	34.6	0.72	1010	0	0	141.	68.	53.	35	25	0.		2.1	470
720	2000	1.28	3.37	46.6	505	88.	17.	4.	0.10	0.30	61.	17.8	0.38	790	0	0	136.	51.	81.	35	25	0.		2.8	330
721	2500	2.02	4.24	27.9	465	94.	12.	0.	0.15	0.42	77.	23.8	0.85	1130	0	0	82.	81.	102.	35	25	0.		2.3	480
722	3000	2.39	4.18	22.1	415	85.	10.	0.	0.19	0.49	76.	26.0	1.18	1200	0	0	65.	96.	101.	35	25	0.		2.2	640
723	3500	2.79	4.18	18.0	340	86.	8.	0.	0.27	0.61	76.	30.5	1.69	0	0	0	53.	111.	101.	35	25	0.		2.1	840
724	4000	2.53	3.31	22.6	405	81.	9.	8.	0.35	0.57	60.	32.7	1.45	0	0	0	66.	101.	80.	35	25	0.		2.5	780
725	2000	0.41	1.07	101.8	128	85.	12.	0.	0.49	0.42	19.	17.3	0.17	0	0	0	298.	16.	26.	35	25	0.		2.4	200
726	2500	0.54	1.12	94.0	72	80.	12.	-4.	0.75	0.40	20.	20.3	0.22	0	0	0	275.	21.	27.	35	25	0.		1.2	200
727	3000	0.84	1.47	75.5	106	78.	13.	0.	0.75	0.38	27.	23.8	0.32	0	0	0	221.	34.	35.	35	25	0.		1.3	235
728	3500	0.94	1.41	75.8	106	79.	13.	0.	0.75	0.39	26.	28.1	0.37	0	0	0	222.	38.	34.	35	25	0.		1.3	280
729	4000	0.99	1.30	68.8	112	75.	11.	0.	0.85	0.45	24.	30.6	0.44	0	0	0	201.	40.	31.	35	25	0.		1.5	320
730	2000	0.71	1.87	70.0	272	80.	15.	0.	0.72	0.32	34.	16.2	0.23	0	0	0	205.	29.	45.	35	25	0.		2.6	230
731	2500	1.22	2.57	37.7	315	72.	12.	3.	0.82	0.40	47.	18.4	0.49	0	0	0	110.	49.	62.	35	25	0.		1.8	340
732	3000	1.53	2.68	34.4	336	72.	12.	0.	0.85	0.41	49.	21.8	0.63	0	0	0	101.	61.	65.	35	25	0.		1.8	400
733	3500	1.75	2.62	32.4	330	74.	11.	1.	0.90	0.46	48.	26.2	0.81	0	0	0	95.	70.	63.	35	25	0.		1.9	460
734	4000	1.65	2.16	42.1	283	80.	11.	0.	0.75	0.47	39.	32.4	0.77	0	0	0	123.	66.	52.	35	25	0.		2.2	480
735	2000	1.33	3.49	43.8	590	85.	17.	3.	0.21	0.30	63.	17.3	0.40	0	0	0	128.	53.	84.	35	25	0.		3.0	330
736	2500	1.77	3.72	32.1	320	100.	11.	0.	0.67	0.45	68.	25.4	0.79	0	0	0	94.	71.	90.	35	25	0.		1.8	460
737	3000	2.19	3.83	20.7	218	75.	10.	-2.	0.71	0.50	70.	22.7	1.10	0	0	0	61.	88.	92.	35	25	0.		1.1	620
738	3500	2.40	3.60	16.5	192	76.	7.	5.	0.82	0.68	65.	26.8	1.63	0	0	0	48.	96.	87.	35	25	0.		1.3	820
739	4000	2.39	3.14	21.9	268	77.	8.	6.	0.84	0.59	57.	31.1	1.42	0	0	0	64.	96.	76.	35	25	0.		1.7	770
740	2000	0.30	0.79	139.0	32	109.	10.	20.	0.15	0.51	14.	21.5	0.15	400	0	0	406.	12.	19.	35	25	0.		1.0	200
741	2000	0.70	1.85	84.6	110	106.	14.	15.	0.13	0.35	34.	20.9	0.25	540	0	0	247.	28.	45.	35	25	0.		1.4	230
742	2000	0.41	1.09	90.7	135	78.	12.	3.	0.84	0.41	20.	15.4	0.17	405	0	0	265.	17.	26.	35	25	0.		2.2	200
743	2500	0.60	1.26	84.1	65	79.	13.	-4.	0.86	0.39	23.	19.5	0.23	515	0	0	246.	24.	30.	35	25	0.		0.9	200

TABLE 6 ENGINE OPERATIONAL DATA-WATER JACKETED ENGINE (CONT.)

THIS IS A HYDROGEN FUELED RUN

RUN NO	RPM	HP	TORQUE FT-PD	A/F	NOX PPM	% THR	EFBT %	IGN ANG	MA-PR IN-HG	BSFC PPHH	BMEP PSI	AFLO PPH	FFLO PPH	EX-T D-F	CHT D-F	CRT D-F	% STOK	%MAX PWR	%MAX BMEP	INJ-FROM BTDC-ATDC		MBT DEG	GM PER	NOX BHPH	INJCT PRES
744	3000	0.79	1.38	74.8	78	78.	13.	-1.	0.84	0.39	25.	23.1	0.31	610	0	0	219.	32.	33.	35	25	0.		1.0	230
745	3500	0.80	1.20	68.4	91	75.	11.	5.	0.94	0.47	22.	25.8	0.38	690	0	0	200.	32.	29.	35	25	0.		1.2	270
746	4000	0.83	1.09	66.3	70	75.	9.	8.	1.00	0.54	20.	29.5	0.44	760	0	0	194.	33.	26.	35	25	0.		1.0	320
747	2000	0.75	1.97	49.2	272	67.	14.	0.	0.93	0.36	36.	13.2	0.27	660	0	0	144.	30.	47.	35	25	0.		1.9	240
748	2500	1.16	2.44	41.3	258	74.	13.	7.	0.94	0.38	44.	18.4	0.44	830	0	0	121.	46.	59.	35	25	0.		1.6	320
749	3000	1.32	2.32	31.9	242	71.	10.	10.	0.91	0.50	42.	20.9	0.66	960	0	0	93.	53.	56.	35	25	0.		1.5	390
750	3500	1.51	2.26	30.4	242	70.	9.	10.	1.02	0.53	41.	24.2	0.80	1050	0	0	89.	60.	54.	35	25	0.		1.6	460
751	4000	1.50	1.97	40.3	212	78.	10.	10.	0.94	0.51	36.	30.6	0.76	1020	0	0	118.	60.	47.	35	25	0.		1.7	450
752	2000	1.31	3.43	40.0	547	80.	16.	2.	0.45	0.30	62.	15.9	0.40	750	0	0	117.	52.	83.	35	25	0.		2.6	330
753	2500	1.58	3.32	24.2	349	78.	10.	3.	0.84	0.50	60.	19.3	0.80	980	0	0	71.	63.	80.	35	25	0.		1.9	450
754	3000	2.06	3.61	18.5	242	74.	9.	3.	0.81	0.58	66.	22.0	1.19	930	0	0	54.	83.	87.	35	25	0.		1.4	650
755	3500	2.33	3.49	14.7	188	72.	7.	7.	0.95	0.72	63.	24.8	1.69	830	0	0	43.	93.	84.	35	25	0.		1.3	850
756	4000	2.35	3.08	20.5	294	74.	8.	7.	0.96	0.61	56.	29.2	1.42	1140	0	0	60.	94.	74.	35	25	0.		1.8	760

TABLE 7

Comprehensive Exhaust Gas Analysis - Water Jacketed Engine

Run No. & Sample No.	H_2(1)	O_2(1)	N_2(1)	CO(1)	CO_2(1)	PPMC
704	0.41	17.29	80.75	0.000	0.0	15
705	0.45	16.65	81.5	0.000	0.0	13
706	0.36	15.27	82.9	0.006	0.0	44
707	0.27	15.05	83.2	0.006	0.0	25
708	0.36	14.42	83.8	0.004	0.0	29
710	0.50	16.85	81.2	0.000	0.0	14
711	0.45	16.24	81.8	0.000	0.0	18
712	0.45	14.74	82.9	0.006	0.0	29
Blank	0.0	20.21	78.6	0.047	0.0	8

1) Values given are in mol (or volume) %

2) Values given are in PPMC (parts per million on a gram atom carbon per mol of gas basis)

TABLE 8 ENGINE OPERATIONAL DATA-GASOLINE TESTS

THIS IS A GASOLINE FUELED RUN

RUN NO	RPM	HP	TORQUE FT-PD	A/F	NOX PPM	% THR	EFBT %	IGN ANG	MA-PR IN-HG	BSFC PPHH	BMEP PSI	AFLO PPH	FFLO PPH	EX-T D-F	CHT D-F	CRT D-F	% STOK	%MAX PWR	%MAX BMEP	INJ-FROM BTDC	INJ-FROM ATDC	MBT DEG	GM NOX PER BHPH	INJCT PRES
757	2000	1.80	4.71	18.9	405	86.	27.	16.	0.12	0.50	86.	17.0	0.90	960	0	0	125.	72.	114.	0	0	16.	1.7	0
758	2500	2.22	4.65	14.7	635	93.	19.	18.	0.21	0.71	85.	23.1	1.57	1080	0	0	97.	89.	112.	0	0	18.	2.9	0
759	3000	2.53	4.42	13.9	435	92.	17.	23.	0.26	0.78	80.	27.2	1.96	1060	0	0	92.	101.	107.	0	0	23.	2.1	0
760	3500	2.36	3.54	14.7	690	89.	15.	24.	0.35	0.88	64.	30.8	2.09	1100	0	0	98.	94.	85.	0	0	24.	3.9	0
761	4000	2.03	2.66	14.0	260	92.	11.	30.	0.44	1.27	48.	36.2	2.59	1080	0	0	93.	81.	64.	0	0	30.	2.0	0

TABLE 9

Comprehensive Exhaust Gas Analysis - Gasoline Tests

Run No. & Sample No.	H_2 (1)	O_2 (1)	N_2 (1)	CO (1)	CO_2 (1)	Hydrocarbon (2)
757	1.39	4.48	80.2	3.82	9.99	2535
758	0.93	4.17	80.9	2.75	10.62	2290
759	1.52	3.71	79.8	4.24	9.71	2620
760	0.76	3.91	80.9	2.59	12.27	2280
761	2.28	4.58	78.8	5.70	8.95	2660

(1) Values given are in mol (or volume) percent.

(2) Values given are in PPMC (parts per million on the basis of gram atoms carbon per mol of gas.